Planning for biodiversity and cereal production in the Gariep Basin: a conservation perspective

Thesis submitted in partial fulfilment of the requirements for the degree of Masters of Science at the University of Stellenbosch

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DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously, in its entirety or in part, submitted it at any university for a degree.

Signature: **Date: 19th December 2005**

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ABSTRACT

Biodiversity feature richness and cereal production potential increase west to east across South Africa's Gariep basin, the regional focus area in the Southern African Millennium Ecosystem Assessment. Irreplaceability, developed for measuring biodiversity value, provides a unit free, spatially explicit measure that can be used to measure an area's importance in terms of cereal production. It provides a common currency to measure competing land-uses. This study models cereal production potential for four cereal types (maize, millet, sorghum, wheat) and sets three cereal production targets, based on minimum nutritional cereal demands and models of actual consumption rates.

Chapter 2 uses C-Plan to determine irreplaceability and compares the irreplaceability values for cereal production potential and biodiversity. Higher cereal production targets increase the irreplaceability of sites for cereal production and increase the number of sites with high irreplaceability for both biodiversity and cereal production. These sites thus have high potential for conflict between these land-uses. Areas of conflict occur primarily across the central eastern region, largely in the grassland biome. The biodiversity features and cereal production potential of these sites are known, thus making potential trade-offs involved in the conservation of these sites explicit.

Sites with conflict potential can be avoided using area selection algorithms that maximise conservation target achievement while minimising the cost to cereal production. C-Plan's simple iterative heuristic approach to minimising costs succeeds in avoiding some areas of conflict potential but more complex algorithms provide better solutions. The simulated annealing algorithm available in another conservation planning software platform, MARXAN, offers a more complex consideration of penalties and costs associated with meeting conservation targets and minimising cereal production costs. Chapter 3 finds that the balance between the penalties for not achieving all biodiversity targets and those for exceeding the cereal cost thresholds in MARXAN are critical, impacting the achievement of certain biodiversity feature targets. Important penalties include the conservation feature penalty factor, the cost threshold, and the cost threshold control parameter. MARXAN generates numerous solutions for a single problem, providing a measure of a site's selection

frequency over a number of runs. The central eastern region has highest variability in selection frequency where both cereal production and biodiversity irreplaceability are high. As cereal production targets increase, sites in this region become more difficult to avoid and trade-offs are unavoidable.

Comparing the software, chapter 4 concludes that the relationships between the inputs and planning parameters on outputs are crucial for effective conservation decision making. C-Plan's sensitivities are restricted to the combination size and site selection rules. MARXAN requires numerous input parameters that collectively provide more variable outputs. Further documentation on best and current practices in MARXAN, sensitivities of conservation outputs to input parameters, and awareness of these sensitivity in capacity building exercises are required to guide decision makers. Irreplaceability allows the comparison of two different objectives and the potential trade-offs that might exist. Explicit inclusion of cereal production potential into systematic conservation planning frameworks generates more cost effective and socially acceptable reserve solutions that strengthen the partnership between conservation and civil society.

Key Words: *conservation planning, biodiversity, cereal production, irreplaceability, trade-offs, opportunity costs, MARXAN, C-Plan.*

Beplanning vir biodiveristeit en graanproduksie in die Gariep opvanggebied: 'n bewarings perspektief.

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UITTREKSEL

Landbouproduksie en biodiversiteitsbewaring kompeteer tradisioneel om land terwyl biodiversiteit en graanproduksie ook toeneem van wes na oos oor die Gariep opvangsgebied. "Onvervangbaarheid" is 'n eenheidsvrye maatstaf, ontwikkel vir die meet van biodiveriteitswaarde, is ruimtelik spesifiek en kan ingespan word vir die bepaling van die belang van 'n gebied vir graanproduksie. Die studie gebruik 'n graanproduksiemodel, wat die produksiepotensiaal van vier graansoorte (mielies, giers, sorgum and koring) modeleer en drie graanproduksiedoelwitte stel. Die doelwitte is gebaseer op die minimum graanaanvraag en twee modelle van graanverbruik.

Onvervangbaarheid is bepaal met "C-Plan" sagteware en die gegenereerde graanproduksie "onvervangbaarheidswaardes" is ruimtelik vergelyk met biodiversiteit onvervangbaarheidswaardes. Hoër graanproduksiedoelwitte verhoog die onvervangbaarheid van areas vir graanproduksie. Dit verhoog ook die aantal areas met 'n hoë onvervangbaarheid vir biodiversiteitsbewaring en graanproduksie, en verhoog dus die aantal areas met 'n hoë landsgebruik konflik-potensiaal. Sulke konflikgebiede val primêr in areas met hoë graanproduksiepotentiaal (bv. die sentraal-oostlike gebiede van die opvangsgebied - grootliks in die grasveld bioom). Die biodiversiteitskenmerke en graanproduksiepotentiaal van die areas is egter bekend, en maak die potensiële afspeling tussen bewarings- en produksie doelwitte haalbaar.

Areas met konflik potentiaal kan vermy word deur optimerings keuringsalgoritmes, wat strewe om biodiversiteitsbewaringsdoelwitte te behaal terwyl kostes ten opsigte van alternatiewe landsgebruike ge-minimaliseer word, te gebruik. C-Plan volg 'n iteratiewe heuristiese benadering om kostes te verlaag en slaag daarin om moontlike konflik areas te vermy. Optimeringsalgoritmes verskaf egter beter oplossings. MARXAN gebruik 'n gesimuleerde anneuliese algoritme wat meer komplekse probleme omtrent biodiversiteitsbewaring en graanproduksie kan oplos. Die sensitiwiteit van algoritme parameters, wat die balans tussen biodiversiteitsdoelwitte en die koste-drumpelwaardes vir graanproduksie bepaal, is ondersoek. Drie beplannings parameters is gebruik: die bewaringsdoelwit-boete-drumpelwaarde, die koste-drumpelwaarde en die koste-

drumpelwaarde-kontrole-parameter. Resultate toon hoe die balans tussen die boetes vir die nie behaling van biodiversiteitsdoelwitte en die oorskreiding van graanproduksie koste-drumpelwaardes, kritiek is. MARXAN produseer meervuldige goeie oplossings vir 'n probleem, wat die frekwensie waarmee individuele gebiede oor alle oplossings geselekteer word, aandui. Die grootste ruimtelik variasie tussen oplossings was in die sentraal-oostlike dele van die opvangsgebied, waar graan produksiepotentiaal en biodiversiteitskenmerke albei hoog is. As graanproduksiedoelwitte verhoog, raak areas in die ooste van die opvangsgebied toenemend moeilik om te vermy. Afspelings tussen doelwitte in hierdie areas raak dan onvermydelik.

Die vergelyking tusen "C-Plan"en MARXAN maak dit duidelik dat die verwantskap tussen insette en beplanningsparameters van uitsette van kritieke belang is vir effektiewe bewaringsbeplanning. By C-Plan word dit beperk deur die kombinasie grootte en die reëls ingespan tydens die seleksie proses. In MARXAN word verskeie inset parameters benodig, wat meer veranderlike uitsette lewer. Die keuse oor welke sagteware platform ingespan moet word hang af van verskeie faktore, maar beter dokumentasie van beste praktyke, kennis rondom die sensitiwiteit van bewaringsuitsette vir inset parameters, en bewusmaking onder gebruikers word benodig.

Die vermoë om gebiede direk te vergelyk in terme van hul onvervangbaarheid vir biodiversiteitsdoelwitte en graanproduksiedoelwitte, maak konstruktiewe afspelings tussen kompeterende landsgebruike moontlik. Die insluiting van graanproduksiepotentiaal in 'n bewaringsbeplanningsraamwerk demonstreer verskillende oplossings wat onderhandelinge rondom die daarstel van meer koste effektiewe en sosiaal aanvaarbare bewaringsplanne kan aanhelp.

Sleutelwoorde: *bewaringsbeplanning, biodiversiteit, graanproduksie, onvervangbaarheid, afspeling, geleentheidskostes , MARXAN, C-Plan.*

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DISCLAIMER

This thesis consists of a series of chapters that have been prepared for future submission to a scientific journal. To standardise between chapters and because they have not yet been submitted to any one journal, the formatting style of *Conservation Biology* is used. Overlap between chapters may occur to secure publishable entities.

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Chapter 4

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Table 2 Summary of results for reserve solutions selected using two different planning software algorithms and three different conservation objectives. Results are given in terms of cost to cereal production potential, representation of biodiversity feature targets, number of sites required and the overlap with sites of highest cereal production potential.

CHAPTER 1

General Introduction

The conservation of biodiversity is a complex task, requiring the consideration of numerous dynamic and interlinked biological, social and economic concerns. The benefits of conserving biodiversity in relation to the important links between biodiversity, ecosystem services and human well-being have long been undervalued and ignored by policy- and decision makers (Cirone & Duncan 2000). This is because the direct and indirect benefits of biodiversity are difficult to measure and are limited by either the expression of biodiversity value and opportunity costs in different currencies (e.g. dollars, species, tons of food) or by the reliance of economic valuations to facilitate comparative analyses (En Chee 2004). Biodiversity has also been undervalued due to the fact that the conservation of biodiversity often seems to come at a greater cost to alternative land-uses. Many such land-uses are essential to providing basic social and economic benefits also important to human well-being, such as food production. These benefits are often also easier to quantify than the benefits of maintained ecological integrity and biological diversity on agricultural productivity. The challenge of finding a comparable valuation approach poses a limiting factor for the integration of social and economic parameters in biodiversity conservation planning (Nagendra 2001).

Increasing concern over the consequences of rapid biodiversity degradation and loss of ecological integrity on human well-being have resulted in attempts to incorporate biodiversity priorities into policies, decisions and actions across a range of sectors (Cirone & Duncan 2000; Wackernagel et al. 2002; Wynberg 2002; Wilkinson 2003). The need to explicitly investigate the relationship between biodiversity, ecosystem services and human well-being was the main focus of the recently completed Millennium Ecosystem Assessment (MA 2003; MA 2005). This internationally organised and supported (UNEP, IUCN, World Bank, WRI and others), multi-scale assessment intended to improve management of ecosystems by meeting the needs of decision-makers and the public for scientific information about the links between ecosystem change and human well-being (see Ayensu et al. 2000; Faith & Walker 2002; MA 2003; Bohensky et al. 2004; Mooney et al. 2004; Mooney et al. 2005; Stokstad 2005). The assessment focused on the condition or health of ecosystems, the anticipated consequences of change in past, present and future ecosystem services on human well-being, and potential response options at local, national, or global scales that will improve human well-being and contribute to poverty alleviation (Faith and Walker 2002; Bohensky et al. 2004; Mooney et al. 2005; Stokstad 2005). Approximately 30 sub-global assessments were conducted, one of which was the Southern African Millennium Ecosystem Assessment (SAfMA) that assessed three core ecosystem services (food, water and services linked to biodiversity) at three spatial scales (Bohensky et al. 2004). Variability in the supply of and demand for ecosystem services was evident across all scales (Scholes and Biggs 2004), as was the need for trade-offs between ecosystem services, biodiversity and human well-being (Faith & Walker 2002; Bohensky et al. 2004).

This thesis (*Planning for biodiversity conservation and cereal production in the Gariep basin: a conservation perspective*) makes use of the data collated and lessons learnt in the SAfMA subglobal assessment, picking up on the need for developing trade offs between human well-being, biodiversity and one of the ecosystem services assessed, namely food production.

SAfMA used cereal production potential as a surrogate of food production. On the scale that is necessary to meet South Africa's cereal demands, intensive agricultural practises are used (Scholes & Biggs 2004). Such practises are seldom conducive to conserving biodiversity features that occur on the land. But, cereal production is vital for human survival as well as essential for socio-economic development (Daily 2000; Rockstrom & Gordon 2001). It can therefore not be ignored in conservation assessments. However, the simultaneous consideration of features as diverse as cereal production and biodiversity is still limited by the lack of a common currency in which to compare them. We propose that basic minimum cereal consumption demands can be used to determine targets for cereal production and that maps of cereal production potential can be utilised, in a similar way as maps of species and vegetation distributions, to calculate the irreplaceability of areas to cereal production targets (see van Jaarsveld et al. 2003). Irreplaceability, although originally developed in the conservation field, provides a unit free ratio that can be useful in the broader field of opportunity costs, and irreplaceability can feasibly be generated for any type of biodiversity feature regardless of its position in nature's hierarchy (structure, function, composition) (van Jaarsveld et al. 2003). Using the concept of irreplaceability, areas important for meeting cereal production targets are comparable with areas important to meeting conservation targets. This allows for the spatially explicit consideration of two different land-use sectors, biodiversity conservation and cereal production, in a common currency and for areas important to both sectors to be identified as areas of possible trade-offs.

The value of a systematic framework that can quantify the costs involved in conserving or utilising areas and identify areas with potential for conflict based on the importance of the area for two different objectives is enormous. Such systematic evaluations that take into account other social and economic concerns of the SAfMA study area could improve the viability, efficiency and effectiveness of conservation plans (Nagendra 2001; Stewart & Possingham 2002; Luck et al. 2004; Moore et al. 2004). Areas with potential for conflict between biodiversity and another land-use sector frequently require the prioritisation of that area for conservation action. This will mean foregone opportunity costs to alternative land uses. However conservation planning algorithms, which exist to assist in the selection of representative reserve systems, are sometimes able to avoid areas of conflict while still achieving all biodiversity conservation targets (Balmford et al. 2001; Faith & Walker 2002; Wessels et al. 2005). Numerous algorithms exist in a variety of conservation planning software platforms. Simple heuristic algorithms work to a certain extent to minimise opportunity costs in representative reserve selections, however more complex algorithms can find better solutions.

This thesis focuses on the application of two of the most common, freely-available conservation planning software platforms that are current widely used amongst conservation planners in South Africa: C-Plan and MARXAN. C-Plan calculates the irreplaceability of an area, which is then used to select areas using simple iterative heuristic algorithms and has been in fairly common usage for some years. MARXAN is a conservation planning software platform that uses near-optimal algorithms to select areas and is increasingly being used. These software platforms are inherently different in their approach to solving the problem of selecting representative reserve systems while avoiding conflict with other land uses. Here we explore the ability of these software platforms to select representative reserve systems while avoiding conflict with land uses such as cereal production potential and evaluate the relative strengths and weaknesses of these applications. The selection of conservation areas that can potentially consider both human cereal demands as well as targets for biodiversity conservation in quantitative terms can significantly enhance the ability of conservation planners to negotiate in terms that are socially and economically intelligent and acceptable. Explicit accounting for human needs in conservation plans will promote a stronger partnership between conservation and civil society and improve the viability of conservation plans at the implementation stage (Nagendra 2001, Postel 2003).

Systematic Conservation Planning

Conservation planning is a branch of conservation biology that identifies options and priorities for conservation in a spatially explicit fashion (Driver et al. 2003), or the means by which all that conservation science and practice knows about regional biodiversity is amalgamated into a single plan to conserve the remaining biological diversity. The locations of many existing conservation areas was rarely determined through conservation planning and are rarely in regions that are also suited for agriculture, forestry or urban development (Rouget et al. 2003a). Historically, many were located on an *ad hoc* basis, biasing existing conservation land to remote, rugged, scenic areas, areas of marginal economic value, areas that contain charismatic species or endemic diseases, or areas that have limited commercial potential (Soule & Sanjayan 1998; Cowling et al. 1999; Reyers & van Jaarsveld 2000; Reyers et al. 2001; Margules et al. 2002; Pfab 2002; Sierra et al. 2002; Rouget et al. 2003a). The cumulative representation of regional biodiversity in these established reserve systems is often poor (Lombard et al. 1999; Rodrigues et al. 1999), and in fact can increase the cost of establishing a representative reserve system (Pressey & Tully 1994; Rouget et al. 2003a). With human populations and demands placing increasing pressure on the remaining natural land and limiting the options for achieving biodiversity targets, there is an evident need for strategic approaches that optimize biodiversity conservation and other forms of land use.

Initial area selection approaches were based on scoring systems. Areas of high species richness, high numbers of rare or threatened species, or combinations thereof, that faced some form of threat were given high scores and were in most crucial need of conservation action (Reid 1998; Reyers et al. 2000). The most popular of these scoring systems was the hotspots approach. Although useful at large geographic scales, hotspots ultimately do not provide an efficient, effective or objective solution to conservation scheduling, particularly at finer scales (Reid 1998; Cowling et al.

1999; Lombard et al. 1999; Margules & Pressey 2000; Sarkar & Margules 2002). Emphasis on areas of high diversity, rarity and endemism ignore whether these areas, when combined, represent the full suite of biodiversity components. Over the past two decades the principles of systematic conservation planning, which include quantitative target setting for spatially explicit biodiversity criteria, complementarity, representivity and persistence, have set systematic conservation planning apart from other forms of planning (Rodrigues et al. 2000a).

Systematic conservation planning provides the best platform for mainstreaming biodiversity across a variety of sectors with proven transparency and defensibility regarding the information it uses (Rodrigues et al. 2000a, Driver et al. 2003). Its principles and advantages have been well documented by scientists and practitioners and the review by Margules and Pressey's (2000) clearly outlines the framework of systematic conservation planning which follows six distinct stages (Box 1). Aspects of steps 1 to 4 that are relevant to the present project are expanded upon in the sections below. This framework outlines the rules for selecting conservation areas that efficiently, both in technique and in terms of ensuring biodiversity viability and persistence, select areas that can achieve the goal of biodiversity representation while taking into account the role of existing conservation areas (Williams 1998). Of importance, is that systematic conservation planning is data driven and heavily dependent on the identification of suitable biodiversity surrogates and on the setting of biodiversity conservation targets.

Compiling Biodiversity Data

Biodiversity itself is a complex notion (Noss 1990) that refers to structural, functional and compositional components of a nested hierarchy, which comprises levels from alleles to kingdoms and includes the diversity of interactions and processes at all levels (Noss 1990; Meffe & Carroll 1994; Sarkar & Margules 2002). It is therefore not easily measured and surrogates of biodiversity pattern and process are frequently sought to assist in determining which areas would contribute most efficiently and effectively to conserving it (Howard et al. 1998; Sarkar & Margules 2002; Lawler et al. 2003). Biodiversity surrogate measures provide an estimate of the similarities and differences between the biodiversity resources of different areas (Freitag et al. 1998; Gaston & Spicer 1998; Reyers et al. 2000; Reyers et al. 2001; Sanderson et al. 2002; Sarkar & Margules 2002; Williams et al. 2002).

Biodiversity pattern

Candidates for surrogate biodiversity measures include sub-sets of species composition and distribution, higher-level biodiversity organisation or environmental factors which include data on higher taxa (e.g. families or genera), vegetation types, remote sensing classes, geological, climatic and terrain data (Noss 1990; Williams 1998; Reyers & van Jaarsveld 2000; Sarkar & Margules 2002; Wessels et al. 2003).

Box 1: Steps in the Systematic Conservation Planning process (Extracted from Margules and Pressey (2000))

1. Compile data on the biodiversity of the planning region

· Review existing data and decide on which data sets are sufficiently consistent to serve as surrogates for biodiversity across the planning region.

2. Identify conservation goals for the planning region

· Set quantitative conservation targets for species, vegetation types or other features (for example, at least three occurrences of each species, 1,500 ha of each vegetation type, or specific targets tailored to the conservation needs of individual features).

3. Review existing conservation areas

· Measure the extent to which quantitative targets for representation and design have been achieved by existing conservation areas.

· Identify the imminence of threat to under-represented features such as species or vegetation types, and the threats posed to areas that will be important in securing satisfactory design targets.

4. Select additional conservation areas

· Regard established conservation areas as 'constraints' or focal points for the design of an expanded system.

· Identify preliminary sets of new conservation areas for consideration as additions to established areas.

5. Implement conservation actions

· Decide on the most appropriate or feasible form of management to be applied to individual areas (some management approaches will be fallbacks from the preferred option).

· If one or more selected areas prove to be unexpectedly degraded or difficult to protect, return to stage 4 and look for alternatives.

6. Maintain the required values of conservation areas

· Set conservation goals at the level of individual conservation areas (for example, maintain seral habitats for one or more species for which the area is important). Ideally, these goals will acknowledge the particular values of the area in the context of the whole system.

· Implement management actions and zonings in and around each area to achieve the goals.

· Monitor key indicators that will reflect the success of management actions or zonings in achieving goals. Modify management as required.

Although the approach has produced mixed results, the most common surrogate of biodiversity pattern has been the species richness and distribution of well recorded taxa (indicator taxa) - (Lombard 1995; Csuti et al. 1997; van Jaarsveld et al. 1998; Reyers & van Jaarsveld 2000; Reyers et al. 2000; Margules et al. 2002; Sarkar & Margules 2002; Williams et al. 2002; Gaston & Rodrigues 2003; Lombard et al. 2003). Species distribution data are often problematic in many respects (Reyers & van Jaarsveld 2000; Reyers et al. 2000; Rodrigues et al. 2000a; Reyers et al. 2001; Sarkar & Margules 2002; Williams et al. 2002; Lombard et al. 2003; Wessels et al. 2003). The scale at which data are collected is often too coarse and stem from incomplete inventories. Data are only available as presence data thus providing no information on abundance or true absences and often have sampling bias towards species that are easy to observe or have well-established taxonomies. Species distribution data also provide only a snapshot of the species pattern in time and space.

As an alternative to species data, surrogates derived from environmental data are often relatively cheap to survey (Williams 1998). They can provide more effective conservation of ecosystem processes (Williams 1998; Sierra et al. 2002; Williams et al. 2002) and serve to represent another level of biodiversity (Sarkar & Margules 2002; Wessels et al. 2003). However, representation at lower levels of biodiversity organization needs to be considered as it may vary by taxonomic group and thus, surrogates of environmental data may best be used in conjunction with species data (Williams 1998; Pressey et al. 1999; Fairbanks & Benn 2000; Reyers et al. 2001; Gaston & Rodrigues 2003; Lombard et al. 2003; Moore et al. 2003). In recent conservation plans, available data have been supplemented with expert opinion, an approach that has been used in South Africa in a few instances (Chown et al. 2001; Cowling et al. 2003a; Driver et al. 2003; Driver et al. 2005). Ideally investment should be put into obtaining better data (Balmford & Gaston 1999) with focused and integrated effort from taxonomists to assist in rectifying current data problems (Golding & Timberlake 2003). This would contribute substantially to the success of conservation planning efforts but limited time, expertise and financial resources, in addition to increasing rates of habitat destruction, make it an urgent task to select and conserve areas now.

Biodiversity Process

At the very basis of systematic conservation planning is the intention to establish a reserve system that conserves a representative sample of a region's biodiversity that maximizes its long-term conservation, subject to socioeconomic constraints (Ferrier 2002). To achieve this, reserve systems should not only represent as much of the biodiversity pattern as possible, but also take into account reserve design and biodiversity processes that promote the long-term persistence of biodiversity (Cowling et al. 1999; Margules & Pressey 2000; Ferrier 2002). This will require due consideration of the vulnerability of biodiversity to threats, reserve size and connectedness, and the inclusion of surrogates of ecological and evolutionary processes responsible for maintaining and sustaining biodiversity pattern (Cowling et al. 1999; Ferrier 2002; Rouget et al. 2003a).

Ecosystem processes are determined by the existence and interplay between intrinsic factors (e.g. variation in abundance, distribution or dynamics of regional biota) with extrinsic factors (e.g. climatic and geophysical conditions) - (Mace et al. 2005). Ecosystem properties and processes are more compactly referred to as ecosystem functions, which may include ecological interactions, species migrations, metapopulation dynamics, pollination, dispersal, fluxes in biotic and abiotic conditions, temporal viability of populations and population processes (Balmford et al. 1998; Cowling et al. 1999; Rodrigues et al. 2000b; Pfab 2002; Reyers et al. 2002). These can broadly be defined as "the capacity of natural processes and components of natural or semi-natural systems to provide services and goods" (Jewitt 2002). Ecosystem services are thus the net product of all processes and are defined in the Millennium Ecosystem Assessment as "the benefits people obtain from ecosystems" (MA 2003). These include cultural services (such as spiritual, recreational, and cultural benefits), provisioning services (such as food and water), regulating services (such as flood and disease control), and supporting services (such as nutrient cycling and carbon sequestration) (Daily 2000; Rockstrom & Gordon 2001; MA 2003).

Approaches focused on the maintenance of processes have included using biodiversity pattern as a surrogate by looking at design criteria, process-specific design criteria and specific spatial components associated with processes (climatic refugia, transition areas, climatic gradients) (Reyers et al. 2002; Rouget et al. 2003a; Pressey et al. 2003). In the absence of any other data, surrogates of biodiversity pattern (such as species or vegetation type richness, also called alpha (α) diversity) are assumed to adequately represent dynamic features of biodiversity function, even when not explicitly targeted (Pressey et al. 2003). Many processes are also assumed to be accommodated by considering reserve design issues, such as size and connectivity, rather than specific locations (Cowling et al. 2003a). The design of reserves can positively impact on the maintenance of viable populations, interspecific interactions, regular and irregular faunal movements, disturbance regimes and resilience to climate change (Cowling et al. 1999; Cowling et al. 2003a). Attempts to include specific spatial components associated with ecological and evolutionary processes have also been attempted (Cowling et al. 1999; 2003a). These spatial components included edaphic interfaces, entire sand movement corridors, whole inter-basin riverine corridors, upland-lowland interfaces, upland-lowland gradients and macroclimatic gradients (Cowling et al. 1999; Cowling & Pressey 2001; Cowling et al. 2003a; Rouget et al. 2003b). Other approaches to addressing the issue of persistence have included the assessment of the probability of persistence for valued features in the selection procedure (Williams & Araujo 2000). Assessments of the rarity or abundance of biodiversity features may be included to improve the effectiveness of reserve systems by considering the long-term probability of persistence (Rodrigues et al. 2000b). However reliable abundance data are often not available. Another attempt to ensure persistence is by considering beta (β) diversity (the turnover of biodiversity features along environmental gradients) - (Fairbanks & Benn 2000; Reyers et al. 2002). The assumption however, that any of these surrogates are adequate measures of a regions importance to biodiversity process, is one that has not been tested and is difficult to assess (Margules & Pressey 2000).

The inclusion of surrogates of ecosystem processes in conservation planning is still in its infancy, but paying more attention to measuring the functional components of biodiversity and including them into conservation frameworks, is likely to benefit biodiversity assessments, prediction, understanding and foresight, and contribute to more effective biodiversity conservation planning (Constanza et al.1997; Cowling et al. 1999; Margules & Pressey 2000; Noss 2000; Reyers et al. 2002). The ability of a system to adapt, change and cope with cyclical, stochastic and long term changes, such as climate change is increased if ecosystems retain their functional integrity (Cowling et al. 1999; Loreau et al. 2001).

Choosing biodiversity surrogates

Our ability to measure biodiversity is filtered by the data and information available. The comparison of diversity between regions changes as more or better information is considered in addition to original measures (Eiswerth & Haney 2001). Different measures will provide different indications of the integrity of ecosystems. The selection of surrogates to use in any given context will depend on the region, reliability and availability of data as well as the conservation objectives (Eiswerth & Haney 2001). These should always be stated explicitly (Williams et al. 2002).

All surrogates have the same inherent failings in that they routinely simplify the complexity of biodiversity by leaving out certain aspects and approximating others (Sarkar & Margules 2002; Balmford et al. 2005). Techniques and measures have improved with enhanced satellite technology, biodiversity inventories and ecological understanding, and will continue to do so. But a combination of surrogates, from many levels of the biodiversity hierarchy, are likely to provide the best approach to measuring the biodiversity value of an area (Williams 1998; Fairbanks & Benn 2000; Eiswerth & Haney 2001; Reyers et al. 2002; Gaston & Rodrigues 2003; Wessels et al. 2003). The identification of appropriate biodiversity surrogates is particularly crucial in developing countries where limited resources, burgeoning threats and frequently *ad hoc* existing reserve networks are a reality (Sierra et al. 2002), but the option of waiting for tested, accurate and reliable surrogate measures is unrealistic as policymakers require practical and defensible recommendations now (Balvanera et al. 2001).

Setting biodiversity targets

Conservation targets are a fundamental, distinguishing aspect of systematic conservation planning as they increase the reliability, repeatability and objectivity of the approach. Targets are the quantitative expression of the conservation goals of a region and ideally express the level of representation required for a biodiversity feature to persist with a certain probability over a particular time frame (Gaston et al. 2002). Targets can include population level targets for species, areal extent of vegetation types or habitats, proportions of spatial components of processes, or numbers of landscape features such as wetlands (see Pressey et al. 2003 for a review of targets).

Setting conservation targets is no trivial matter as goals and values are not universal, biological patterns and processes are notoriously variable and complex at all levels of organisation, and there is little or no scientific basis that establishes what optimal targets may be (Soule & Sanjayan 1998; Williams 1998; NSW 2001; Sarkar & Margules 2002). Even the frequently recommended 10% representation target is not fully defensible and is effectively a rule of thumb (Soule & Sanjayan 1998; Lombard et al. 1999; Reyers et al. 2001; Gaston et al. 2002; Sierra et al. 2002; Wackernagel et al. 2002; Wessels et al. 2003). Most important is that conservation targets are as explicit as possible and that they attempt to be proactive rather than reactive (Williams 1998; Balvanera et al. 2001). The prospects for achieving one goal may need to be weighed up against the possible diminished prospects of achieving others as the inclusion of more surrogates of biodiversity pattern and process will likely increase the area required to achieve the targets set. This is even more so when focusing on the inclusion of rare features and identifying areas important to spatial components of ecological and evolutionary processes. This points to a trade-off between the effectiveness and the efficiency in area selection (Pressey et al. 1999; Rodrigues et al. 2000b; Desmet & Cowling 2004) as well as a trade-off with other land use sectors.

Conservation Value

While using a measure of an area's diversity, endemism or rarity provides no indication of its contribution to achieving biodiversity targets in relation to other areas, using the data and conservation targets described above, areas of importance to conservation (i.e. high conservation value) can be identified. A means of assigning conservation value to an area is through the application of the principle of complementarity and the calculation of irreplaceability (Pressey et al. 1993; Pressey 1999; Ferreir 2000; Araujo 2002; Margules et al. 2002).

Complementarity is the principle of adding places by maximising the number of new biodiversity features (Sarkar & Margules 2002). It is different to scoring techniques in that it recognises the identity of individual features in an area and calculates their relative contribution to attaining the conservation goal (Pressey et al. 1993; Araujo 2002). Areas are selected in a step-wise fashion based on a criterion, such as richness or rarity. After the selection of an area with the highest biodiversity feature value, richness for example, subsequent selections are made based on their complementarity to areas already selected until the pre-defined conservation target has been attained (Reyers et al. 2000; Sarkar & Margules 2002). The complementarity approach is favoured as it explicitly captures the differences between places and reaches the best compromise between species representation, particularly of rare and endemic species, and land-use efficiency (Williams et al. 1996; Reid 1998; Williams 1998; Lombard et al. 1999; Reyers & van Jaarsveld 2000; Reyers et al. 2000; Sarkar & Margules 2002).

Complementarity is used to calculate irreplaceability. Irreplaceability is a measure of the relative importance of an area for achieving conservation targets, or otherwise described as the likelihood that an area will be needed for achieving specified conservation targets (Pressey 1999; Ferrier et al. 2000; NSW 2001). Irreplaceability is an expression of an area's conservation value or options, in that it measures the flexibility with which an area can be substituted for another while still achieving conservation targets (Pressey et al. 1993). The original calculation of irreplaceability was a combinatorial problem, but much work has gone into making it a predictive approach that has culminated in a powerful statistical approach whose calculations and advantages are outlined by Ferrier et al. (2000) - (Pressey 1999; NSW 2001).

This approach to assigning conservation value has the advantage of being able to deal with large datasets consisting of numerous different biodiversity surrogates (Sanderson et al. 2002). The approach is transparent, flexible, relatively simple and allows for patterns of irreplaceability to be quickly calculated, displayed, recalculated and redisplayed as new conservation decisions are made. This is imperative to facilitating interactive assessment of priority areas, investigating the effects of changes in goals or data and remaining flexible to different solutions and trade-offs (Csuti 1997; Pressey et al. 1997; Williams 1998; Pressey 1999; Ferrier et al. 2000; Pressey & Cowling 2001). It is these characteristics that have helped the global application, legal standing and usefulness of systematic conservation planning. Irreplaceability maps create a platform from which competing land uses and trade-offs between different conservation options can be evaluated (Costanza 1997; Balvanera et al. 2001; Sarkar & Margules 2002).

Identifying threats to persistence: Cereal Production

Food is an essential requirement for human survival and is largely produced through intensive, and to a lesser extent extensive, agriculture. The agricultural sector plays an important role not only in food provision and contributing to food security, but also in contributing to job creation, livelihoods, raw materials, foreign exchange and a country's Gross Domestic Product (GDP) - (Bohensky et al. 2004). In South Africa, only 14% of the total surface area is suitable for crop production and since the 1960s approximately 80% of the estimated arable land has been cultivated (Kamara & Sally 2003; Bohensky et al. 2004). Horizontal expansion of agricultural production has been restricted by the limited arable land remaining uncultivated and by the need to increase yield per hectare and reduce the inefficient expansion of extensive, low productivity farming onto marginal lands (Biggs & Scholes 2002). Additionally, changes in South Africa's agricultural sector since apartheid have encouraged the intensification and productivity increase per hectare, primarily in response to new tax and labour laws (Bohensky et al. 2004).

In southern Africa, cereals supply a dominant proportion of the necessary carbohydrate and protein dietary requirements of the average individual with the recommendation that cereals make up as much as 54% of daily dietary requirements (FAO and WHO 1998; Bohensky et al. 2004). Daily dietary requirements are recommended by the World Health Organisation (WHO) as the consumption of 2100 kilocalories per day, including 48g and 56g of protein daily for the average woman and man respectively (Scholes & Biggs 2004). The staple cereal type varies in different areas, but maize is highly favoured in much of southern Africa. Cereals such as wheat, sorghum and millet play a lesser, although still important role, and a number of other crops are also produced for domestic consumption and export (Bohensky et al. 2004). Whichever the cereal, grains can be easily stored and transported, and they remain an essential source of nourishment in all of southern Africa. It is necessary to point out that although they are dependent concepts, food production is a far cry from food security (Bohensky et al. 2004), which is determined by multiple drivers and in South Africa is influenced by issues such as HIV/AIDS, access to supplies, and household income (Bohensky et al. 2004). Thus, although there is sufficient cereal production, there is no guarantee that everyone has access to sufficient food.

With increased use of irrigation, fertilisers and genetically modified plants, food production is not entirely limited by the natural productivity of the land. But increases in production capacity are also not totally divorced from ecosystem integrity and have not occurred without costs to ecosystems (Bohensky et al. 2004). The public and scientists often view agricultural food production in a negative light. Particular concerns have been over the "mining" of soil, extraction of large quantities of water for irrigation, use of pesticides and fertilisers, deterioration of natural rangeland and impairment of other ecosystem services (Daily et al. 1998; Ashby 2001; Bohensky et al. 2004; Mooney et al. 2005; Stokstad 2005). Such concerns can easily go unrecorded and many of these costs ultimately feed back to impact on agricultural productivity. But the agricultural sector has largely viewed food production as separate from ecosystem integrity (Daily et al. 1998; Ashby 2001). However, with the change in government in South Africa and the development of the Strategic Plan for South African Agriculture (NDA 2001), as well as the Policy of Agriculture in Sustainable Development (NDA 2003), the emphasis has changed to the integrated role that economic, social and environmental concerns have in sustainable development. Attempts to limit the detrimental effect on the natural resource base, and encourage sustainable development, as mandated by the South African constitution, has led to several initiatives to improve or regulate different aspects of agriculture (NDA 2001). Such legislation acknowledges the links between ecosystem health-integrity and agricultural productivity, and provides a basis for easier negotiation around agriculture-environment issues, particularly when it comes to making difficult trade-off decisions. Thus assessments that explore the relationship between cereal production and biodiversity highlight areas important to each of these sectors and identify areas where there is a potential for conflict would be valuable.

Trade-offs

The issue of trade-offs in relation to competing land-use sectors or the efficiency and effectiveness of reserve selections has already been mentioned. The traditional concept of a conservation area serves to halt or limit natural resource use that, at current and future human population demands, threatens the persistence of biodiversity. To a large extent trade-offs have become the rule in conservation planning as the challenge of meeting human needs, for example cereal production, will inevitably come at a cost to biodiversity and other ecosystem services (Daily et al. 1998; Ashby 2001; Faith & Walker 2002). As such, conservation area allocations have serious socio-economic and political implications (Margules & Pressey 2000). Different values, competing objectives and diverse stakeholders and actors make trade-offs an inherent part of decision making, and often make the process of choosing between trade-offs a contentious one (Bohensky et al. 2004).

When considering trade-offs between ecosystem services, such as food and biodiversity, the choice inherently becomes one of current and long-term needs. Choices may be required between meeting the current needs of society versus the needs of ecosystems and the maintenance of human well-being over extended spatial and temporal scales (Bohensky et al. 2004). Such choices will not be easy to make. In an area where food insecurity is still a reality, weighing up the short-term and long-term advantages of agriculture will be difficult and it is common that the cost of such decisions is not born equally by the population (Adams et al. 2004). By considering trade-offs and their implications explicitly, the process of choosing between options and considering the likely consequences of alternative choices could be greatly aided (Bohensky *et al.* 2004). In order to avoid a situation where biodiversity in productive landscapes remains unprotected in the face of continuing disturbance, transformation and fragmentation, a better understanding of the costs to both biodiversity and cereal production potential may help us identify and deal with the necessary trade-offs required.

Acknowledgement of the need to consider both biodiversity and land uses that use natural resources is perhaps evident in the mainstreaming of biodiversity and conservation concerns in other land use sectors, where legislation that mandates Environmental Impact Assessment's and Strategic Environmental Assessment's is increasingly becoming the norm (Cowling et al. 2003b, Driver et al. 2003). This means that conservation planners not only have to consider the constraints imposed on biodiversity conservation due to other land uses, but that other land use sectors increasingly have to contend with the constraints placed upon them through the existence of areas important for biodiversity conservation (South African National Environment Management Biodiversity Act 2004; Victor & Keith 2004). Building a conservation area network requires reaching conservation targets through the accumulation of land as efficiently as possible within the constraints imposed by competing socio-economic land uses (Possingham et al. 2000; McDonnell et al. 2002; Stewart et al. 2003). Within this arena of limited land and increasing constraints, lies a range of area selection opportunities that are best identified using conservation planning tools that can consider multiple objectives.

Conservation Planning software

The large number of biodiversity features and planning units for which conservation values have to be determined necessitates the need for conservation planning software. Interactive conservation planning programs serve as tools to aid decision makers in determining options for achieving conservation goals (flexibility) and to identify areas of high conservation value (irreplaceability) that require priority protection. At the basis of reserve selection algorithms is the minimisation of area required to meet defined conservation targets (Pressey et al. 1997; Leslie et al. 2003; Stewart et al. 2003), which can be defined as a mathematical problem and was first described as a minimum representation problem (Kirkpatrick 1983). The foundation for the problem is the reality that although biodiversity conservation objectives would maximise the area to be conserved, social, economic and management constraints limit the land available (Possingham et al. 2000; Stewart et al. 2003). A number of different software platforms exist for solving this problem and are based on three strategies available for solving conservation area selection problems, but which represent two families of algorithms: optimization and heuristics. These algorithms differ in their usability, strengths, weaknesses, ability to consider multiple objectives and outputs.

Optimisation algorithms (available in C-Plex – ILOG 1997-2000), although very powerful and capable of considering multiple objectives simultaneously, are more seldom used in conservation planning. In the past they have been prohibitively time consuming (although see Rodrigues and Gaston 2002) and in general require investment in resources and expertise (Moore et al. 2003). Heuristic algorithms, although unable to guarantee an optimal solution, can compare favourably with optimal solutions (Moore et al. 2003). Heuristic algorithms used in area selection problems can be sub-divided into those developed by operations researchers and conservation researchers (Moore et al. 2003). The latter, designed heuristic algorithms that use a list of rules to select sets of areas iteratively, most of them based on their complementarity and irreplaceability (such as C-Plan - NSW 2001), to provide simple and relatively fast solutions that are easily communicable (Moore et al. 2003). Constraints, other than the number of planning units selected, are considered iteratively, as a secondary factor when solving between ties during the area selection process. Algorithms developed by operations researchers, which include simulated annealing (used in MARXAN - Ball & Possingham 2000), neural networks and genetic algorithms, have been around for much longer than those designed by conservation researchers and their performance and limitations have been well studied and defined (Moore et al. 2003). These algorithms can simultaneously consider multiple constraints and provide a useful quantitative estimate of the quality of their solutions. Heuristic algorithms are found in conservation planning software platforms such as C-Plan and MARXAN, which are freely acquired and have been utilised in conservation plans in South Africa.

Study objectives

The main objective of this thesis is to assess conservation and cereal production target achievement in the Gariep Basin of South Africa. The thesis has three areas of focus. First, we aim to compile the necessary spatially explicit data for this objective and set realistic targets for biodiversity features and cereal production potential. Existing data on the biodiversity of the planning region that are sufficient in scale and consistency to serve as biodiversity surrogates will be compiled. Explicit, quantitative conservation targets for these surrogates will be guided by existing targets and best understanding of the minimum requirements to ensure the persistence of the biodiversity features over time. Spatially explicit data on cereal production potential will be compiled and quantitative targets that realistically estimate the demands for cereal production in the SAfMA Gariep-basin study area will be compiled and defined. With spatially explicit data and quantitative targets, we propose the use of irreplaceability (calculated using C-Plan – NSW 1999) as a common currency that will enable the comparison of the importance of that site or unit, in the context of the planning domain, for achieving biodiversity conservation targets or cereal production targets. We thus explore the overlap of areas that are important to each objective and identify areas where there is potential for conflict. The use of irreplaceability for cereal production potential and the future potential application of this approached will be discussed.

The second part of this thesis aims to explore the target achievement of both biodiversity conservation and cereal production potential in the selection of biodiversity conservation areas using two conservation planning software platforms that are commonly used in South Africa. These software platforms differ in the algorithms used to select areas for conservation and thus differ in the way multiple objectives are considered. It is important to understand the ability of these software platforms to select representative reserve systems while avoiding conflict with cereal production potential and to evaluate the relative strengths and weaknesses of their application. Chapter 2 applies a very simple approach available in C-Plan (NSW 1999; Pressey 1999), which provides the simplest first attempt at trying to maximise the achievement of conservation targets and minimise the cost to cereal production potential. C-Plan uses an iterative heuristic to select sites based first on their biodiversity irreplaceability value, and selects sites with the lowest cereal production potential when there is a tie in the biodiversity irreplaceability value. This guides the selection of areas with high irreplaceability values, considering cereal production as a secondary objective. While such a simple approach will help to some extent, it is likely that other algorithms could provide better solutions. Chapter 3 explores the application of a more complex algorithm available in MARXAN (Possingham & Ball 2000), which uses simulated annealing and simultaneously considers the objectives of biodiversity and cereal production targets achievement. MARXAN provides multiple, near optimal solutions to a conservation problem. Trade-offs in the achievement of goals for both objectives under different scenarios of cereal demand will be assessed.

Finally, the outputs of these two different popular conservation planning software platforms, and their implications in terms of what they tell the user about conservation options and land-use trade-offs will be compared. Practicalities in terms of data, expertise and processing power requirements will also be evaluated. The third part of this thesis thus (chapter 4) compares the two approaches with the intent of being practically useful for conservation planners when trying to plan for conflicting objectives. The solutions generated will have important implications for conservation planning, the future of biodiversity conservation and the success of conservation plans. It is hoped that this thesis will illustrate the value of irreplaceability as an approach that can be simply but effectively used to highlight areas of importance to targets other than just biodiversity conservation targets, and to identifying areas of potential conflict. Selecting areas for conservation, while considering competing objectives, is a complex problem. Through exploring the use of two popular conservation planning software platforms, this thesis hopes to contribute towards understanding some of their practical merits and disadvantages when exploring conservation planning problems with competing objectives and trade-offs analysis.

Summary of key objectives

Main objective: To assess conservation and cereal production target achievement in the Gariep Basin of South Africa.

Sub Objectives:

1) To determine surfaces of biodiversity and cereal production distribution in the study region.
2) To determine targets for biodiversity conservation and cereal production in the region.
3) To identify areas important for achieving targets for biodiversity conservation and targets for cereal production (irreplaceability)
4) To investigate the spatial congruence of areas important to biodiversity conservation and important to cereal production.
5) To assess trade offs between biodiversity conservation and cereal production using systematic conservation planning.
6) To investigate the value of different conservation planning platforms for use in conservation planning and trade offs achievement.

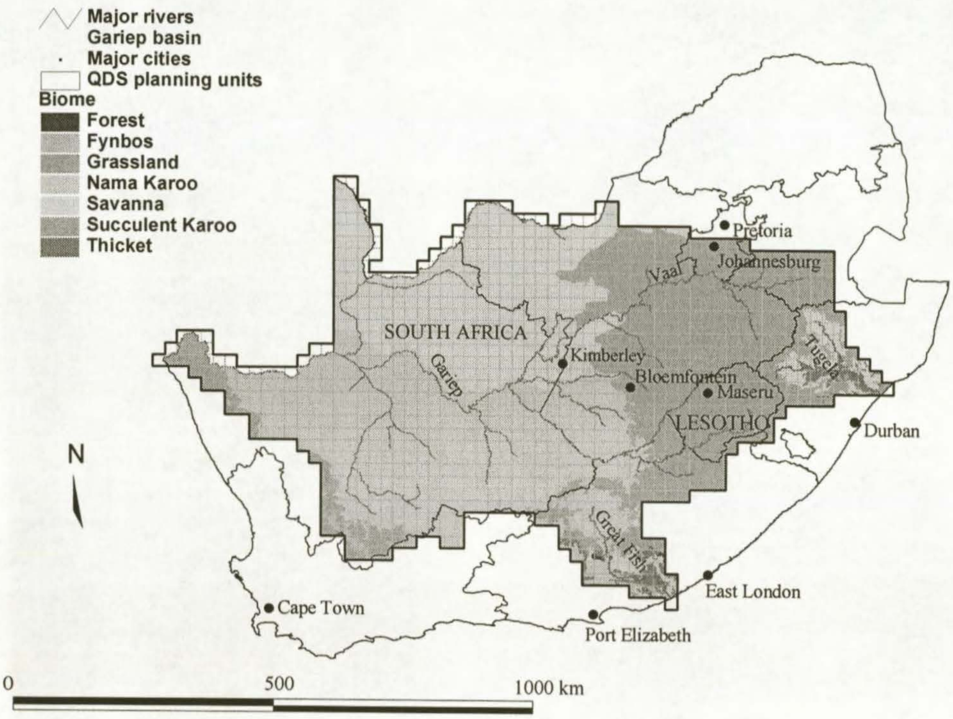

*Figure 1. The Gariep basin of South Africa and Lesotho, regional study region of the Southern African Millennium Ecosystem Assessment (*SA*f*MA*), showing major towns and rivers, vegetation biomes and the division of the area into quarter degree grid squares.*

Study area

The study region was the focus area of the Gariep basin sub-global assessment of the Southern African Millennium Ecosystem Assessment (SAfMA) completed in 2004 (Bohensky et al. 2004). The study area is partially defined by the ecological boundaries of the Senqu-Gariep-Vaal river system, referred to as the Gariep basin. Major water transfer schemes connect the Gariep basin with two additional primary catchments (which are included in the study area): the Tugela River in KwaZulu-Natal Province and the Great Fish River in the Eastern Cape. The basin encompasses an area of 683,600km^2 and comprises approximately 60.7% of South Africa (SA) and the entirety of Lesotho.

The Gariep River is characterised by increasing aridity and semi-arid to arid vegetation to its exit into the Atlantic on the west coast of South Africa, bordering Namibia. Irrigated farming (although threatened by water extraction higher up the river) and the mining of diamonds and other minerals are the main land uses in the western section of this river. To the east, increasing agricultural potential, grasslands and savanna characterise the landscape. Mining on the east rand at the turn of the 19th century led to the development of the Gauteng province into a major urban and commercial centre in the country. Water from the Gariep and Tugela rivers originates in the Lesotho highlands, characterised by high altitude montane grasslands and natural isolated forests in gullies and ravines. Large extents of this region have high afforestation potential. The Fish River is a more forested landscape with similarly high afforestation potential but much higher utilisation by the many people that populate this largely poor, rural area. The Gariep Basin contains all 7 of South Africa's biomes, the largest being the savanna, grasslands and Nama karoo biomes, which differ markedly in terms of their biodiversity composition, threatening processes and conservation efforts. The region as an ecological entity is marked by a distinctive west-east gradient of precipitation which is shadowed by a similar increase in primary productivity, human population density, vegetation cover and species richness (Bohensky et al. 2004).

The Gariep basin is home to more than 20.9 million people (StatsSA 2003; Lesotho Bureau of Statistics 2002). In addition to the volume of water the Gariep basin delivers, the third largest discharge in southern African, the basin is recognised as the locus of southern Africa's socio-economic powerhouse and development potential. Of high importance though is the so-called "bread-basket" of southern Africa in the mid eastern region of the basin, which produces much of the area's cereal. Additional pressures placed on the land and natural resources of the basin include urbanisation, mining developments, grazing, afforestation, alien invasives and altered flow and water quality regimes (Bohensky et al. 2004). The threat of desertification, especially in the more arid western regions, combined with highly variable and unpredictable precipitation patterns that occur across the region and the significant threat of climate change, with predicted contraction of the Succulent Karoo biome (Rutherford et al. 1999; van Jaarsveld & Chown 2000; Bohensky et al. 2004) all pose serious threat of land degradation and concern for land managers. Indeed these have the potential to seriously compromise the provision of essential ecosystem services required for the maintenance of human well-being.

Planning units, biodiversity features and feature targets

The study area was divided into 1110 quarter-degree square (QDS) grid cells (15' x 15' ~ 700km^2; hereafter referred to as a site). All data were generalised to a common resolution of a QDS to conform to the resolution of the species distribution data.

Biodiversity feature data included distribution data on amphibians (Southern African Frog Atlas Project - Minter et al. 2003), birds (Southern African Bird Atlas Project - Harrison et al. 1997), mammals (Freitag & van Jaarsveld 1995, Keith 2004) and vegetation types (Low & Rebelo 1996). In total, there were 10 amphibian (2 endemic, 0 CR), 63 bird (0 endemic, 4 CR species), 21 mammal (3 endemic, 3 CR) species and 40 vegetation types included in the analysis. These databases were considered of suitable spatial resolution, taxonomic completeness, and with limited bias over the national geographic extent (Rouget et al. 2004). In line with national conservation plans and assessments in South Africa (Rouget et al. 2004), only species categorized as "species of special concern" were included in the analysis (Rouget et al. 2004). These are species that are either endemic to the region or threatened, according to the IUCN classifications of Critically Endangered (CR), Endangered (EN), Vulnerable (VU) and Near Threatened (NT) (IUCN 2001). Marine, vagrant and exotic species were excluded from the analysis and biodiversity features with more than 95% of their distribution falling outside of the basin were considered marginal and also excluded from the analysis.

Defining targets for biodiversity features is largely subjective. In the absence of abundance and population data for species distributions, a single occurrence per species is commonly used as a representation target. Also in line with national conservation plans and assessments, targets for CR species were increased to full representation in acknowledgement of their low numbers, their severe vulnerability and the urgent need for the conservation of these species. Other species of special concern (endemic, EN, VU and NT) remained at a single representation (see Rouget et al. 2004). Vegetation targets were adjusted by the natural rarity (NR) of each vegetation type and a measure of threat within the vegetation type (TH), determined by the formula described in Reyers (2003) and detailed in the chapters:

Production data and targets

Dryland suitability data for certain cereals are available from the Agricultural Research Council, but provide no quantitative data on production potential and are limited to regions of suitability that were investigated within the confines of commissioned projects. A model holding more potential for inclusion in this study was one developed by Scholes and Biggs (2004), for the SAfMA, that modelled total annual cereal production potential (CPP) at a 5km resolution based on simple crop growth models, adjusted to observed production in South Africa as given by the Food and Agriculture Organisation statistics (FAO 2003) database, and restricted to cultivated areas (Scholes & Biggs 2004). This model is described in detail in the chapters. Three targets were determined for cereal demand. The first is based on the basic minimum requirements based on World Health Organisation (WHO) recommendations. The remaining two were determined using a study by Nel and Steyn (2002), which provides two estimates of average adult consumption, calculated using two different methods to determine combined estimates for different population groups, for three of the four cereals modelled in this study.

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CHAPTER 2

Planning for biodiversity and cereal production in the Gariep basin, South Africa

ABSTRACT

Agriculture and biodiversity conservation have long been competing land-uses. This is particularly the case in the Gariep basin of South Africa, a regional focus area of the Southern African Millennium Ecosystem Assessment. The need to integrate conservation and food production is an important one, both globally and in the Gariep. However, the absence of a common currency with which to measure and integrate these two sectors hampers such efforts. The measure of irreplaceability, developed for measuring biodiversity value, provided a unit free, spatially explicit measure which could be used to measure an area's importance in terms of cereal production. This study uses a model of cereal production potential for four cereal types (maize, millet, sorghum and wheat), and sets three cereal production targets, based on minimum nutritional cereal demands and two models of actual consumption rates. Irreplaceability is determined using C-Plan and cereal production potential irreplaceability values are directly comparable with biodiversity irreplaceability values generated using species and vegetation distribution data and national conservation targets. The Gariep basin produces enough cereal to meet the minimum nutritional cereal demands of its human population. Higher cereal production targets based on real consumption rather than modelled needs increase the cereal production irreplaceability of sites. This increases the number of sites with a high potential for conflict with biodiversity conservation objectives. Areas of conflict lie largely in the central eastern regions of the grassland biome. A simple iterative heuristic available in C-Plan succeeds in avoiding some areas with potential for conflict, but more complex approaches would find better solutions. The ability to compare parcels of land with one another in terms of both their biodiversity value and their value to cereal production, provides a better understanding of the potential trade-offs, and would aid negotiation towards more cost effective, socially acceptable solutions. This would also strengthen the partnership between conservation and civil society.

INTRODUCTION

The Millennium Ecosystem Assessment has shown that humans have had a greater impact on the world's ecosystems in the last 50 years than at any other time in human history (MA 2005). The Millennium Ecosystem Assessment was a global study, which explored the links between human well-being, the status of ecosystems and the prospects for their sustainable use. It found that biological diversity has declined rapidly and continues to decline at a rate exceeding background extinctions rates due to human activities. In addition to the unprecedented losses of whole species or populations of species, many ecosystem services are severely degraded or being utilized unsustainably. More than 60% of the ecosystem services assessed were in a declining condition (MA 2005). Even with focused response actions, the drivers of change in those ecosystem services emphasised in the Millennium Ecosystem Assessment (such as biodiversity, water, food or fuelwood supply) are likely to continue or accelerate in the future (MA 2005). The unsustainable utilization of ecosystem services and continued biodiversity losses will impact upon the capacity of ecosystems to provide services, and threaten the well-being of future human generations (Bohensky et al. 2004).

The increased demand on ecosystem services, which results from the growing human population and increased per capita consumption, is the major indirect driving force responsible for the continued and increasing pressure on the earth's ecosystems and biodiversity (MA 2005). Direct drivers of change include pollution, overexploitation of species, climate change, invasive alien species and habitat transformation (through land use change, alteration of the physical attributes of rivers, and water extraction) (MA 2005). Although other direct drivers are likely to have an increased impact in the future (namely climate change, pollution and the spread of invasive alien species – MA 2005), habitat transformation remains an important driver of change, particularly in developing countries (Green et al. 2005). The most extensive driver of habitat change is agriculture. The conversion of land to agriculture has been greater in the 30 years after 1950 than in the 150 years between 1700 and 1850 (MA 2005). An estimated quarter of the earth's surface is now covered by cultivated systems (MA 2005), which has reduced the extent of natural habitats by more than 50% (Green et al. 2005). Estimates indicate that up to 30% of irrigated land is moderately to severely degraded, and that this percentage is still increasing in some biomes (Pimm 2001; MA 2005). Agriculture has significantly affected all biogeographical regions, placing pressure on biodiversity and ecosystem function (Matson et al. 1997; NDA 2001; Conway & Toenniessen 2003; Donaldson 2003; MA 2005).

Humans have benefited from the large-scale conversion of land to agriculture and developments in agriculture have increased the productivity of land, which has reduced the overall area required to meet current human population demands. But with increasing human populations and standards of living, agriculture is still projected to be one of the biggest pressures on biodiversity now and in the future (Fairbanks et al. 2000; Pimm 2001; Green et al. 2005; MA 2005).

Additionally, the costs to ecosystems are not only related to the direct impact of land cover change, but also from the extensive environmental change caused by water extraction for irrigation and the increase in nutrient-associated pollutants (MA 2005). Although the need to meet existing human food demands encourages the immediate utilization of resources, it is in the long-term interests of society to maintain ecosystem integrity and reduce the impact on and unsustainable use of resources. Decisions regarding utilization and conservation of biodiversity, ecosystems and services they provide, will inevitably involve difficult trade-offs (MA 2005). Such trade-offs involve considerations about competing goals. In assessing such trade-offs, decision-makers can be greatly aided by integrated conservation and development planning approaches.

Integrated regional planning approaches strive to achieve more balanced regional trade-offs and win-win scenarios (Gelderblom et al. 2002; Balmford 2003; Cowling & Pressey 2003; Faith & McNeely 2005; MA 2005). The retention of potential net benefits of a region is achieved by considering the effect of different land use scenarios on the capacity of a region to balance its competing objectives. Efforts to conserve biodiversity and maintain the integrity of ecosystems are more likely to be successful when incorporated into regional planning and development strategies that take into account other demands on natural resources (Kremen et al. 1999; Faith & McNeely 2005; MA 2005). Equally, development plans can benefit from the inclusion of biodiversity and sustainable use objectives. Agricultural productivity and sustainability could also benefit from the protection of biodiversity and the ecosystem services it provides, such as pollination, pest control, the removal of excess nutrients, soil fertility and protection against soil erosion (MA 2005). Integrated planning focuses on integrating sectors, scales and responses, in a manner similar to the approach adopted by the Millennium Ecosystem Assessment (MA 2005). The analysis of trade-offs between these issues, sectors, scales, and responses can be greatly aided by the qualitative and quantitative valuation of biodiversity and ecosystem services (MA 2005). The integration of conservation with alternative land uses was previously hampered by the expression of biodiversity value and opportunity costs in different currencies (e.g. dollars, species, tons of food) or by the exclusive reliance on economic valuations to facilitate comparative analyses (Nagendra 2001; En Chee 2004).

This study aimed to address this challenge in the integration of biodiversity conservation and cereal production into comparable spatial frameworks in order to evaluate trade offs and the potential for conflict between these two sectors in the Gariep Basin of South Africa. In order to overcome the above problems of comparable measures for biodiversity value and opportunity costs to cereal production, the measure of irreplaceability was applied. Irreplaceability is a measure of the importance of a particular land parcel (further more referred to as a *site*) to achieving an explicit conservation target (Pressey 1998; Cowling et al. 2003). Conservation targets are the quantitative expression of the conservation goals for a biodiversity feature (such as species, vegetation types or ecological processes) in a particular region. They ideally express the level of representation required for a biodiversity feature to persist with a certain probability over a particular time frame (Gaston et al. 2002). Targets can include population level targets for species, areal extent of vegetation types or habitats, proportions of spatial components of processes, or numbers of landscape features such as wetlands (Pressey et al. 2003). The notion of irreplaceability is an indication of the lost conservation options if a particular site were further degraded or converted (thus losing its biodiversity features) (Pressey et al. 1993). Irreplaceability provides a site-specific and unit-free value statement derived from the proportional contribution that the biodiversity on a site makes towards a specified regional target. Numerous potential applications of irreplaceability in conservation planning have been identified and it has become an important means for evaluating the biodiversity value of sites (Pressey 1998; Pressey 1999; Margules & Pressey 2000). Although originally developed in the conservation field, this unit free ratio appeared useful in the broader field of opportunity costs, as irreplaceability can feasibly be generated for any type of biodiversity feature regardless of its position in nature's hierarchy (structure, function, composition) (van Jaarsveld et al. 2003).

So in addition to measuring the contribution of site's biodiversity features to a quantitative conservation target, this study proposed to measure the contribution of a site's potential cereal production to a production target determined by human needs. In order to assess the application of irreplaceability in the integration of biodiversity conservation and cereal production the study aimed to collate data on the distribution of biodiversity and cereal production potential in the Gariep basin and set targets for both biodiversity conservation and cereal production. The methods for this are well established in terms of biodiversity data and targets, however models of cereal production potential and cereal needs and consumption rates had to be developed or amended for the calculation of irreplaceability for cereal production. The potential production of four cereal types in the Gariep basin were modelled using an existing model that determines potential yield per unit of farmed land. Production targets for cereal are calculated based on estimates of human requirements and consumption rates.

Using the concept of irreplaceability, areas important for meeting cereal production targets were comparable with areas important to meeting conservation targets. This allowed the spatially explicit consideration of two different land-use sectors, biodiversity conservation and cereal production, in a common currency. Areas important to both sectors were identified as having potential for conflict. Irreplaceability is calculated using C-Plan, a conservation planning tool readily available in South Africa. In line with this study's aim to use existing, easy to use models and techniques, an algorithm available in C-Plan was used to incorporate costs during planning in a simple iterative attempt to find an integrative solution. We propose that the explicit inclusion of a unit-free and therefore comparable valuation of sites, in terms of their contribution to meeting biodiversity targets and cereal production demands, provides an understanding of the potential trade-offs required in the region.

METHODS

Study Area

The Gariep basin occupies an area of 683,600 km^2 incorporating the whole of Lesotho and 60.7% of central South Africa (Fig. 1). It is formed by the Senqu-Gariep-Vaal river system, as well as two primary catchments connected to this system by major water transfer schemes: the Tugela river in KwaZulu-Natal Province and the Great Fish river in the Eastern Cape Province. The region, which is marked by a distinctive west-east precipitation gradient, contains all 7 of South Africa's biomes (Low & Rebelo 1996), although it is predominantly made up of the Nama Karoo, Grassland and Savanna biomes. The Savanna biome is the smallest of these but is the most speciose, containing a fair number of endemic and threatened species. The Grassland biome contains the most endemic and threatened species, with the Drakensberg grasslands being a recognised center of endemism. In spite of this, the Grassland biome has the highest levels of transformation and is poorly protected (Fairbanks et al. 2000; Reyers et al. 2001). The Nama Karoo is the largest biome in the basin. It is the least speciose of the three main biomes, but contains substantial numbers of the region's endemic and endangered species. This semi-arid biome is the least protected of the three main biomes (Reyers et al. 2001).

The Gariep basin is an important socio-economic region in South Africa. The associated pressures of agriculture, urbanization, industrial and mining developments, grazing, afforestation, alien invasion, altered water flow regimes and deteriorating water quality all place pressures on ecosystems (Bohensky et al. 2004). High levels of agriculture in the study area and the associated negative impact on the ecological integrity of the region were highlighted in the regional Millennium Ecosystem Assessment (Bohensky et al. 2004) and in previous studies (Fairbanks et al. 2000, Reyers et al. 2001). Much of the region's indigenous grasslands are reported to be under severe threat (Neke & du Plessis 2004; Bohensky et al. 2004).

Cultivated land in South Africa increased significantly during the last century, to the extent that approximately 80% of estimated arable land is cultivated today (Biggs & Scholes 2002, Bohensky et al. 2004). This increase was especially concentrated in the eastern higher rainfall areas and the extreme southern regions of the country. Expansion of cultivated land has slowed and field crop yields per unit area have grown with improved technology, increased land under irrigation, increased application of fertilizers, pesticides and herbicides, and genetic modification of crops (Biggs & Scholes 2002; Bohensky et al. 2004). It is generally accepted that there is limited potential for further horizontal expansion of cultivated land in the basin (NDA 2001; Biggs and Scholes 2002).

The Gariep basin study area was divided into 1110 quarter-degree square (QDS) grid cells (15' x 15' ~ 700 km^2; hereafter referred to as a site) (Fig. 1). All data were generalised to a common resolution of a QDS to conform to the coarsest resolution of the wild species distribution data.

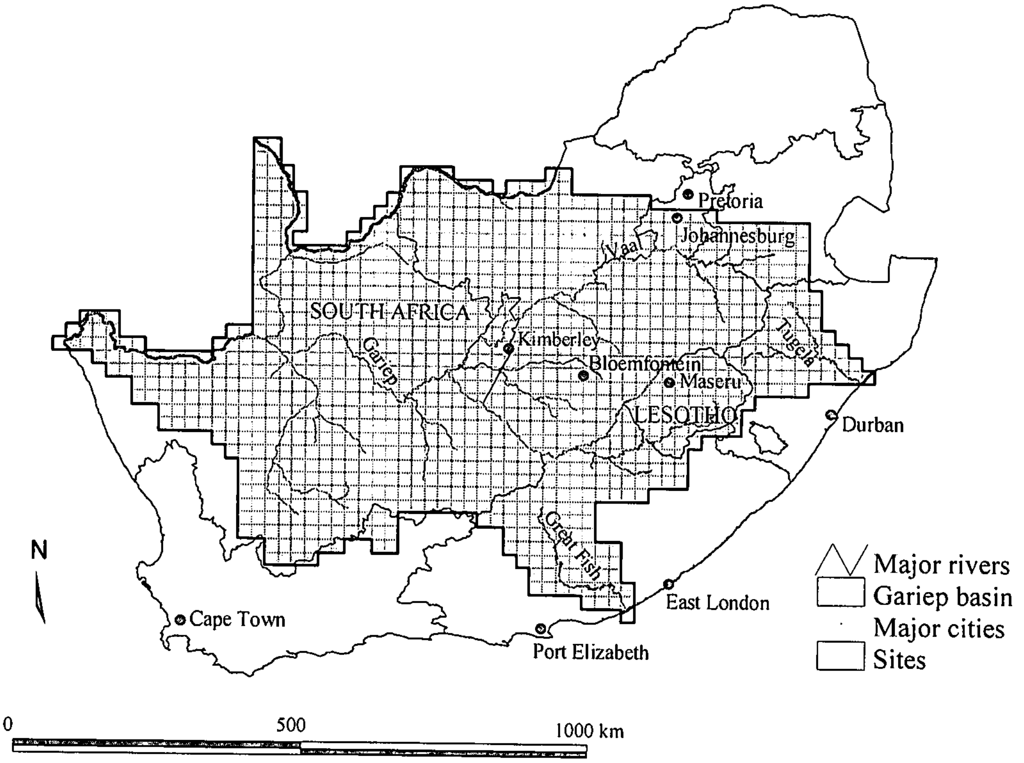

Figure 1. The Gariep basin of South Africa showing the country's provinces, major rivers and cities and quarter degree grid squares (or sites).

Biodiversity data

Biodiversity feature data included distribution data on amphibians, birds, mammals and vegetation types. The Gariep basin holds 40 vegetation types - defined as having "similar vegetation structure, sharing important plant species, and having similar ecological processes" (Low & Rebelo 1996). Species distribution data were collated from the Southern African Frog Atlas Project (Minter et al. 2003), the Southern African Bird Atlas Project (Harrison et al. 1997) and mammal distribution data (Freitag & van Jaarsveld 1995, Keith 2004). These databases were considered of suitable spatial resolution, taxonomic completeness, and with limited bias over the national geographic extent (Rouget et al. 2004). Only those species categorized as "species of special concern" (Rouget et al. 2004) being species either endemic to the region or threatened, according to the IUCN classifications of Critically Endangered (CR), Endangered (EN), Vulnerable (VU) and Near Threatened (NT) (IUCN 2001), were included. Marine, vagrant and exotic species were excluded from the analysis. This is in line with national conservation plans and assessments in South Africa (Rouget et al. 2004). In total, there were 10 amphibian (2 endemic, 0 CR), 63 bird (0 endemic, 4 CR species) and 21 mammal (3 endemic, 3 CR) species included in the analysis. Distribution data on vegetation types were collated from Low and Rebelo (1996). Biodiversity features with more than 95% of their distribution falling outside of the basin were considered marginal and excluded from the analysis.

Biodiversity targets

Defining targets for biodiversity features is largely subjective. Target guidelines for areas are frequently set at a minimum of 10% of a region, be that a habitat type, vegetation type or biome (Pressey et al. 2003). In the absence of abundance and population data for species distributions, a single occurrence per species is commonly used as a representation target. Representation targets were increased to full representation of CR species in acknowledgement of their low numbers, their severe vulnerability and the urgent need for the conservation of these species. Other species of special concern (endemic, EN, VU and NT) remained at a single representation (see Rouget et al. 2004). Vegetation targets were adjusted by the natural rarity (NR) of each vegetation type and a measure of threat within the vegetation type (TH), determined by the formula described in Reyers (2003):

$$\text{TARGETVEG} = 10 \times (1 + \text{NR} + \text{TH}) \qquad \text{(Eq. 1)}$$

where, TARGETVEG is the percentage of the original extent of each vegetation type; NR is measured as $(Am - Ai)/Am$ where Am is the area of the largest vegetation type in the region and Ai is the area of the vegetation type for which the target is being set (Reyers 2003). The South African national land cover database (Thompson 1996; Fairbanks et al. 2000) was overlaid with vegetation data to determine TH. This was calculated as the proportion of a vegetation type affected by transformation and degradation, and was determined by reclassifying the 31 land cover classes into 3 categories of natural, modified and transformed vegetation based on Fairbanks et al. (2000). NR and TH values range from 0 to 1 and final vegetation targets range from 10 to 30% of the original extent of each vegetation type.

Cereal production data

Available data on agricultural arability or dryland suitability say very little about quantitative cereal production values. This limits our ability to set quantitative production targets and to determine the value of areas in terms of cereal production. The opportunity cost for cereal production potential was therefore modeled using the only approach available (Scholes and Biggs 2004). This approach models the total annual cereal production (in million tones - Mt) at a 5km^2 resolution. It is based on simple crop growth models, adjusted to observed production in South Africa as given by the Food and Agriculture Organisation statistics (FAOSTAT) database, restricted to cultivated areas and based on the following equation:

$$\text{Total CP (t)} = \sum_{\text{cereal } \alpha} \left[\left(\frac{\text{Observed total} \alpha \text{ CP (t)}}{\text{Estimated total} \alpha \text{ CP (t)}} \right) \times \text{Estimated } \alpha \text{ CP (t) spatially distributed} \right]$$

(Eq. 2)

where CP is cereal production potential, t is the period of 1995-1999 over which all statistics were averaged and α signifies a specific cereal crop. The observed total CP as a proportion of the estimated total CP in South Africa provides an adjustment factor that corrects the estimated cereal production per crop over the spatial extent of the basin to fit the observed average total production for each cereal (obtained from the FAOSTAT database; FAO 2003). The estimated cereal production per crop over the spatial extent of the basin was calculated using the equation:

$$\text{Estimated } \alpha \text{ CP (t)} = \text{Cultivated area (ha)} \times \text{Fraction planted to cereal } \alpha \times \text{Maximum yield of cereal } \alpha \text{ (t/ha)} \times f\text{(growth days)}_{\text{cereal } \alpha}$$

(Eq. 3)

where cultivated area was obtained from the sum of all cultivated land classes in the South African National land cover database (Thompson 1996). The assumption is made that agriculture has been practised in South Africa for some time, that commercial agriculture is well established and that therefore, agriculture is not going to experience considerable further extensification, but rather that intensification will be the dominant trend (Biggs and Scholes 2002). A consequence of this however, is that cereal production potential may be slightly underestimated. The fraction of each cereal crop planted is the average area planted per cereal crop divided by the total area under cultivation for that cereal crop, based on data obtained from the FAOSTAT database (FAO 2003). Maximum yields per cereal are those under intermediate input levels given by the Global Agro-Ecological Zones study (FAO and IIASA 2000), where the maximum yields for maize, millet, sorghum and wheat are 5.3, 3.6, 4.6 and 3.4 t/ha respectively. Growth day functions were determined by relating the crop precipitation requirements given in FAO Ecocrop database (FAO 2003) to growth days. The relationship between annual precipitation and growth days was determined by linear regression ($r^2=0.911$, $p<0.001$, $n=429444$):

$$\text{Growth days} = 19.367 + 0.167 \times \text{Precipitation} \tag{Eq. 4}$$

Scaling the cereal productivity by the function of growth days, which is a factor of precipitation and thus varies spatially, generates the spatial distribution of cereal production potential across the Gariep basin.

In the Southern African Millennium Ecosystem Assessment, this model was used to generate cereal production potential surfaces for maize, sorghum and millet. We applied this model to maize, sorghum, millet and wheat. The inclusion of wheat is justified as this cereal makes the second largest contribution to meeting kilocalorie demands from cereal in South Africa (Nel and Steyn 2002). Although treating each cereal crop species separately and evaluating conflict with conservation per crop type would be a preferable approach, this was not possible due to a lack of data on the current spatial distributions of each crop species in the basin. The only spatial data available were for all cereal crop species combined, thus compelling the combination of the four crop species into one composite cereal production potential layer. Although the single layer of production potential was necessary, maize, wheat, sorghum and millet differ in the fraction of land in the basin planted to each cereal, their respective maximum yields and their crop precipitation requirements. Thus calculating each layer separately in the model ensures greater accuracy in determining the cereal production potential surface. The final cereal production potential, at a 5 km^2 resolution, was summed to an estimate of cereal production potential for each quarter degree grid square. The total cereal production potential for the basin was determined as a sum of the cereal production potential in each quarter degree grid square.

Cereal demand

Demand for cereal can be established by determining the contribution of cereals to meeting the minimum daily kilocalorie requirements of the Gariep basin's human population. This is taken as the Recommended Daily Allowance (RDA), assumed to be 2100 kcal/person/day (Scholes and Biggs 2004). At least 54% (1134 kcal/person/day) of these daily requirements are provided by cereal (FAO and WHO 1998; Bohensky et al. 2004). The relative contribution of each cereal crop to this target is multiplied by the population and the number of days in a year to determine the total kilocalorie demand (see Eq. 5). This is divided by the kilocalorie content of each cereal type α, taken from the Global Agro-Ecosystem Zones data (FAO and IIASA 2000), to determine the final cereal requirements in tons per year.

$$\text{Total cereal demand (t/yr)} = K\left[\frac{1134\ \text{kcal/person/day}\times\left(\dfrac{\alpha.\text{Cereal production}}{\text{Total cereal production}}\right)\times\text{Population}\times 365\ \text{days}}{\text{Kcal content } \alpha \text{ cereal (kcal/1000g)}}\right] \qquad \text{(Eq. 5)}$$

where K is the conversion factor from kilograms to tons, the fraction of each cereal produced is based on data obtained from the FAOSTAT database (FAO 2003) averaged over the period 1995 to 1999 and population estimates for the Gariep basin and Lesotho were extracted from the South African population census data (StatsSA 2003) and the Lesotho Bureau of Statistics (2002) respectively.

Equation 5 provides a minimum production demand and the first cereal production target, which is the amount of cereal that needs to be produced to meet minimum human cereal requirements (target 1). However, actual kilocalorie intake can be much higher than the recommended daily allowance.

Estimates of actual consumption rates of the different cereals types provide a more accurate indication of human cereal demand. These estimates were taken from Nel and Steyn (2002). Differences in consumption patterns between the different population groups in South Africa provide estimates of average adult consumption (adult defined as older than 10 years of age). These estimates are calculated using two different methods to determine combined estimates for different population groups. In very simplified terms, Method 1 did not take ethnic group proportions into consideration for each provincial region (province) in South Africa (target 2). Method 2 estimated the food intake per province by taking the proportion of ethnic groups per province into consideration (target 3). These two methods provide different estimates of average adult consumption. Method 2 (Table 1) differs from method 1 in that it estimates higher consumption of wheat and lower consumption of maize and estimates a lower overall target from that calculated using method 1. Nel and Steyn (2002) did not include millet in their models as it was not a commonly consumed cereal type. Millet contributes relatively little to target 1 (0.36%) and it is thus considered acceptable that it is not included in the calculation of targets 2 and 3. Cereals also contribute to protein intake but the total requirements to fulfill protein needs of the population never exceeded those of kilocalorie demands (Table 1) and are thus already met by meeting kilocalorie demands.

Table 1. Calculation of cereal targets given in million tons (Mt) for four cereal types in the Gariep Basin (South Africa) based on minimum daily nutritional requirements (Target 1) and two methods of estimating the actual consumption in South Africa (Targets 2 and 3).

	Maize	*Millet*	*Sorghum*	*Wheat*	*Total*
Production in SA & Lesotho (Mt/yr)	8.290	0.038	0.368	2.172	10.868
Production in SA & Lesotho (g/yr)	7.875E+11	3.690E+09	3.720E+10	2.650E+11	1.093E+12
% of total	72.02	0.34	3.40	24.24	100.00
Contribution to daily protein requirements [a]	21.35	0.10	1.01	7.18	29.64
Cereal protein content (g/1000g)	95	97	101	122	
Total protein requirements (Mt/yr) [b]	1.932	0.009	0.086	0.506	2.533
Production in SA & Lesotho (kcal/yr)	2.951E+13	1.293E+11	1.263E+12	7.255E+12	3.816E+13
% of total	77.34	0.34	3.31	19.01	100.00
Contribution to daily calorie requirements [c]	877.00	3.84	37.55	215.61	1,134.00
Cereal calorie content (kcal/1000g)	3560	3400	3430	3340	
Total calorific requirements (Mt/yr) [b]	2.118	0.010	0.094	0.555	2.777 (Target 1)
Method 1 [d]:					
Average per capita (g/capita/day)	690.06		1.67	152.8	
Average demand (Mt/yr)	5.933		0.014	1.314	7.261 (Target 3)
Method 2[d]:					
Average per capita (g/capita/day)	475.57		1.42	160.63	
Average demand (Mt/yr)	4.089		0.012	1.381	5.482 (Target 2)

[a] *Minimum daily protein requirements from cereal types is 29.64g*

[b] *For the Gariep population of 20.97 million*

[c] *Minimum daily kilocalorie requirements from cereal types is 1134 kcal*

[d] *Extracted from Nel and Steyn (2002)*

The calculation of food demand in the Southern African sub-region is not a simple one, being influenced by complex factors such as politics, global trade trends and weather. There are a number of assumptions made in the calculation of these cereal targets, but it is proposed that the simple calculation of targets be used as a means of exploring the current situation. The first assumption is that every person has the nutritional requirements of an adult (adult defined as older than 10 years of age), which will likely overestimate cereal demand. The second assumption is that all people have equal access to cereal products, which is not the case. Third, the Gariep basin is treated as a closed system, an assumption that is flawed as it ignores cereal imports into and exports out of the basin. However, data on these imports and exports are currently lacking, as are data for cereal demands of non-human consumption (such as livestock feed and seed), which are also excluded here. While these factors are an important part of the economy, contributing to human well-being in the basin, they are more difficult to estimate reliably. As further data become available these may be included into the model to estimate more realistic cereal demands.

Biodiversity and cereal production irreplaceability

Based on the targets set for biodiversity features (species and vegetation types) and for cereal production, the irreplaceability of sites for each of these objectives is calculated using an approach detailed in Ferrier et al. (2000). Ferrier et al. (2000) employ a predictive approach for calculating irreplaceability by estimating the number of times a site is a vital component of a combination of sites that achieve the set target. This number is expressed as a proportion of the estimated total number of representative combinations, which in turn represents the irreplaceability value of the given site. Values range from 0 to 1, with 1 being totally irreplaceable. Sites with an irreplaceability value of 1 are critical for achieving the target, such as a site containing the only known record of a particular species. If a target is equal to or exceeds the available abundance of a biodiversity feature or cereal production potential, all sites that hold that feature or have production potential will be irreplaceable. In the case of biodiversity, lower irreplaceability values represent sites that hold biodiversity features that occur in alternative sites and denote more flexibility in the inclusion of these into possible conservation planning solutions. Lower irreplaceability values for cereal production potential are proportional to their contribution to the total cereal target. Thus, for biodiversity or cereal production, sites with higher irreplaceability values contribute more towards achieving targets and the irreplaceability value is the likelihood that a given site will be required to ensure the regional target is achieved. Irreplaceability was applied to both biodiversity data and cereal production data using the software platform C-plan (NSW NPWS 1999; Pressey 1999) and mapped using ArcView 3.2 (ESRI 1999). Three irreplaceability surfaces for cereal production were generated for each of the three cereal production targets.

Sites with an irreplaceability value greater than 0.5 for cereal production, for each of the three cereal production targets, are plotted against those with irreplaceability greater than 0.5 for biodiversity (see Fig. 2). These sites are also rated according to their likely biodiversity-cereal production conflict potential as implied by their combined irreplaceability scores.

$$\text{Conflict potential} = \text{biodiversity irreplaceability} + \text{cereal production irreplaceability} \quad \text{(Eq. 6)}$$

Sites with a biodiversity irreplaceability value between 0.8 and 1 that, when combined with the irreplaceability value for cereal production potential, have a combined irreplaceability value of between 1.8 and 2 (maximum) represent sites important for both objectives. These are sites with *high conflict potential* that contain high potential opportunity costs for both biodiversity and cereal production. Sites with a combined irreplaceability value between 1.4 and 1.8 have *moderate conflict potential* and those with combined irreplaceability between 1 and 1.4 are deemed to have *low conflict potential.*

Reserve Planning Scenarios

Conservation planners are aware of the fact that the inclusion of costs into conservation plans can help minimise conflict. As many conservation planners in South Africa use C-Plan, we decided to apply a simple iterative algorithm available in C-Plan to include cereal production potential into the planning process. It has been shown that when considering multiple objectives, such as the maximisation of biodiversity representation and minimisation of costs to cereal production potential, more complex algorithms (such as optimisation or simulated annealing) provide better solutions (see chapter 3). The approach used here will not provide the most optimal nor efficient solution to minimising costs while maximising biodiversity representation, but it takes this study one step further in illustrating the potential value of including cereal production potential data into conservation plans.

Two scenarios are posed to explore the use of algorithms to minimise the cost to cereal production potential during biodiversity reserve selection. In each instance areas are selected in a step-wise fashion, with biodiversity irreplaceability re-calculated after each selection. The first step in each scenario requires the selection of the site with the highest irreplaceability score for biodiversity. The first scenario selects sites with the highest irreplaceability to biodiversity until all biodiversity targets are achieved. This is the minimum set of sites required to achieve all biodiversity targets. The second scenario avoids high cereal production areas by breaking ties between sites with equal irreplaceability to biodiversity by selecting the site with lowest cereal production potential. The adjacency of a site to another selected site is used to iteratively resolve ties between sites with the same irreplaceability category and the same cereal production potential.

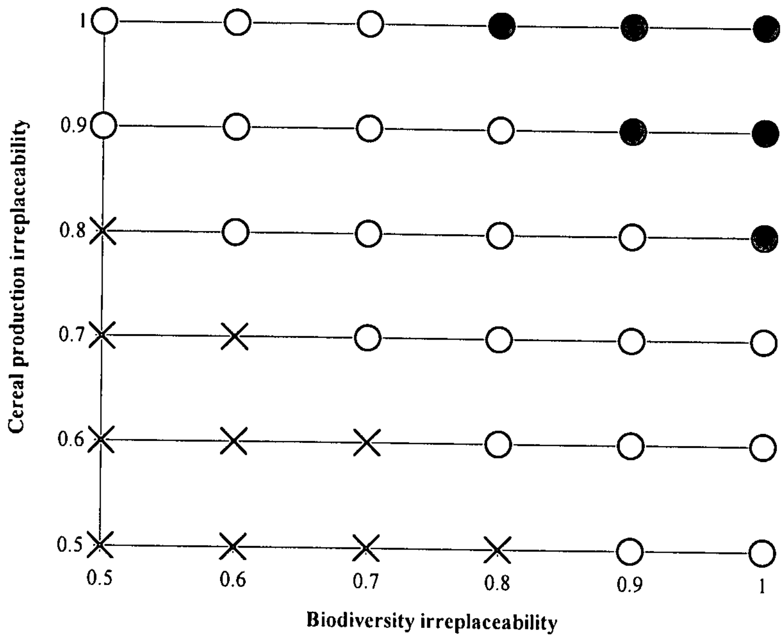

Figure 2. Biodiversity irreplaceability (>0.5) plotted against cereal production irreplaceability (>0.5). The value of their combined irreplaceability was categorised as follows: combined irreplaceability between 2 and 1.8 (closed circles) has a high conflict potential, between 1.8 and 1.4 (open circles) has a moderate conflict potential and less than 1.4 (crosses) has a low conflict potential.

This is a simple, but still common approach to avoiding costs, and represents the only option for minimising costs offered in C-Plan. The second step of planning scenario 2 was conducted outside the C-Plan platform. This is as the calculation of irreplaceability in C-Plan is done to a number of decimal places that would result in very few ties between areas after the totally irreplaceable sites had been selected. Using categories that restrict irreplaceability results to a single decimal results in more ties and allows for the application of the step that seeks to minimise the cost to cereal production more frequently. This approach has been used in previous studies (Wessels et al. 2000).

Reserve solutions are evaluated in terms of their foregone opportunity cost to cereal production, the area required, and the number of sites that fall within the high, moderate and low conflict potential categories.

RESULTS

Distribution of biodiversity in the Gariep basin

Figure 3a shows species richness of species of special concern is highest in the central-eastern region of the Gariep basin. This is largely in the grassland biome, which predominates much of this region (Fig. 3b), has the highest number of vegetation types and has relatively high levels of transformation (Fig. 3c). Transformation in this biome is largely due to agriculture, but also occurs as a result of urban areas, plantations, mines and degradation. High species richness is also found in the south-eastern arm of the basin (along the Fish River catchment) where 6 biomes converge. Current levels of transformation in this region are fairly low. On the very eastern side of the basin, where Thicket, Savanna, Grassland and Forest biomes converge, there are some sites with high species richness. Higher levels of transformation due to afforestation occur in this region. Much of the central regions and western regions of the basin, predominated by the Savanna and Nama Karoo biomes, have lower species richness but also much lower current levels of transformation. The Savanna biome has fairly high levels of degradation.

Cereal Production Potential

Total cereal production potential of the Gariep basin is estimated at just over 5.621 Mt/yr. Modeled cereal production potential (Eq. 2) for the whole of South Africa and Lesotho indicate that the Gariep basin contributes approximately 52% of South Africa and Lesotho's total cereal production potential. The distribution of this production potential (Fig. 3d) is linked to the precipitation pattern, which exhibits a strong west to east gradient. Production potential is also limited to already cultivated land. Therefore, only 51.08% of the sites in the basin have any cereal production potential (potential to produce > 0 Mt/yr cereal) and these lie largely in the eastern half of the basin. Half of this productive land (49.74%) has the potential to produce more than 5000 t/yr.

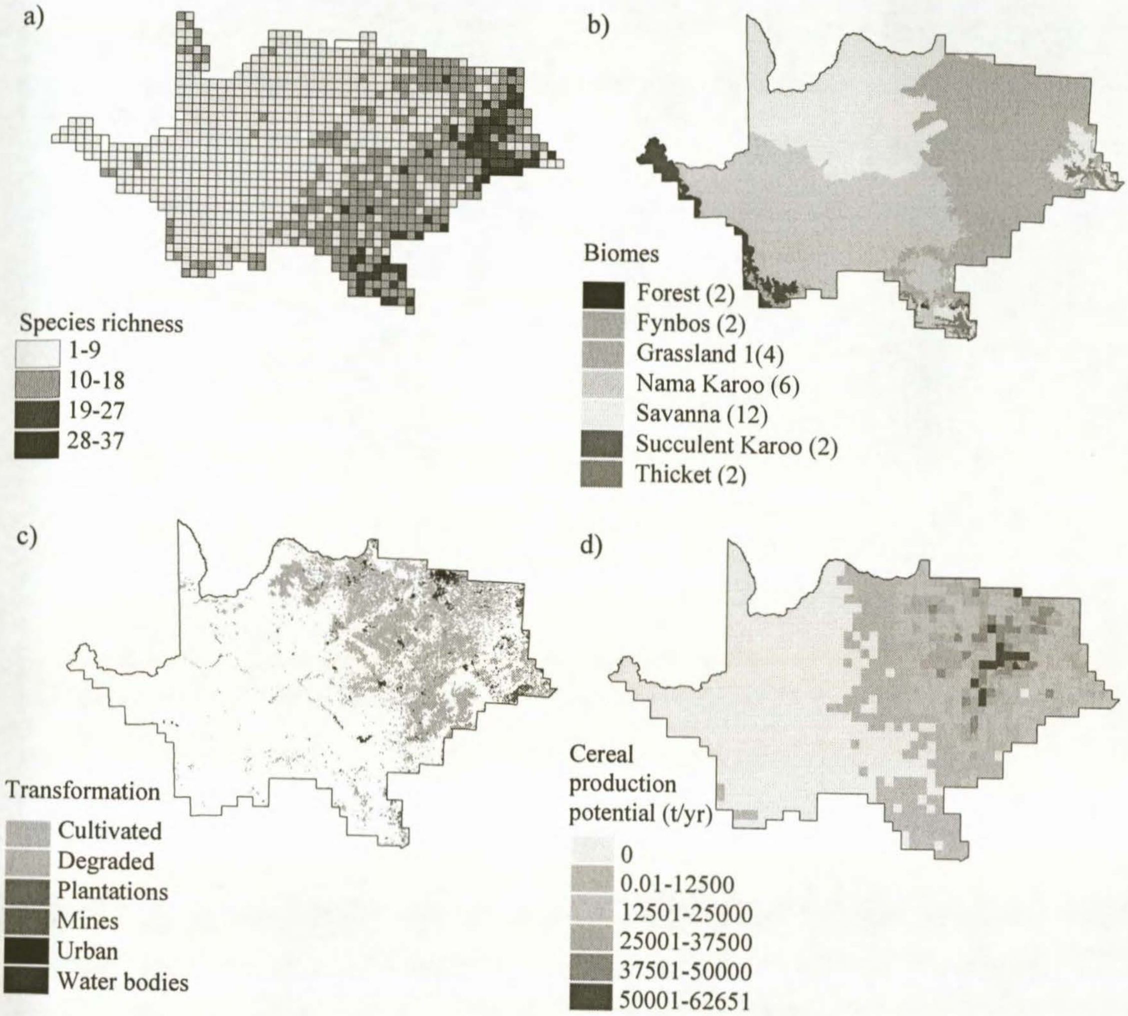

Figure 3. The Gariep basin of South Africa with (a) species richness of species of special concern, (b) biomes (number of vegetation types in parenthesis), (c) types of transformation and (d) cereal production potential.

Land with cereal production potential lies predominantly in the eastern savannas and grasslands of the basin (Fig. 3d). The Grassland biome has the largest area under cultivation, the least remaining natural vegetation and highest cereal production potential (Table 2). Much of this cereal production potential lies in the dry sandy highveld, moist cool highveld and moist cold grassland vegetation types. Other biomes in the Gariep have less than 10% of their area under cultivation and in total contribute less than 10% to the cereal production potential of the basin. The Savanna biome makes the second largest contribution to total cereal production potential, but less than half the biome has any cereal production potential. The Thicket biome is the only other biome that produces more than 1% of the total cereal production potential. Although its area is the third smallest in the basin, it has the second highest percentage of area currently under cultivation. The Nama Karoo biome occupies the greatest area in the basin, but it has little of its area under cultivation, low area extent with cereal production potential and contributes little towards total cereal production potential. The Forest, Fynbos and Succulent Karoo biomes together occupy less than 5% of the basin's area, with very little of their area in the basin under cultivation and together contribute less than 1% to total cereal production potential. While nearly the entire forest biome is estimated to have cereal production potential, only 2.2% of it is cultivated. The high cereal production potential is probably due to the coarse resolution of the study, a factor likely to impact on all estimates of areas under cereal production, especially in the smaller biomes.

Biodiversity and cereal production irreplaceability and conflict potential

Total cereal production potential of the basin exceeds cereal production target 1 (2.779 Mt/yr) and 2 (5.482 Mt/yr) but not target 3 (7.261 Mt/yr) (Table 1). Sites with high irreplaceability values have high cereal production potential, contributing most towards achieving cereal production targets. As only a single feature, cereal production potential, is used to determine irreplaceability, the distribution of sites with high irreplaceability to cereal production potential targets mirrors the distribution of actual cereal production potential. Higher cereal production targets increase the irreplaceability value of all sites that have cereal production potential (Fig. 4a-c). The average irreplaceability value over sites that have cereal production potential is 0.151 at cereal target 1, 0.217 at cereal target 2 and 1 (i.e. irreplaceable) at cereal target 3. There are no sites irreplaceable to cereal production target 1 or 2. As cereal target 3 exceeds the region's total cereal production potential, all sites (567 sites) with some cereal production potential become irreplaceable (Fig. 4c). In terms of biodiversity irreplaceability, 68 (6.13%) of the sites are irreplaceable to achieving conservation targets, 84 (7.57%) sites are highly irreplaceable (i.e. irreplaceability between 0.8 and 1), while 840 (75.68%) sites have an irreplaceability value less than 0.2. A high number of sites irreplaceable to biodiversity targets exist in the eastern grasslands, where there is a confluence of forest, thicket and savanna biomes (Figure 4d).

Table 2. Descriptions of biomes with respect to the percentage area within the Gariep basin, the number of vegetation types, percentage of natural vegetation remaining, percentage under cultivation and the cereal production potential (CPP) across the Gariep basin.

Biome	*Forest*	*Fynbos*	*Grassland*	*Nama Karoo*	*Savanna*	*Succulent Karoo*	*Thicket*
% Area in basin	0.18	0.67	32.95	34.58	27.23	3.03	1.37
Vegetation types	2	2	14	6	12	2	2
% Natural vegetation remaining [a]	86.86	98.11	66.22	97.77	84.68	97.67	81.82
% Basin area under cultivation [a]	2.2	1.32	25.72	1.36	6.54	0.15	7.03
% Basin area with CPP	98.33	36.48	97.12	19.26	42.5	9.76	91.81
CPP (Mt/yr) [b]	0.007	0.004	4.931	0.054	0.545	0	0.079
% Total CPP	0.13	0.08	87.73	0.96	9.7	0	1.41

[a] *Based on National Land Cover Database (Thompson 1996)*

[b] *Cereal production potential total in million tons (Mt) per year*

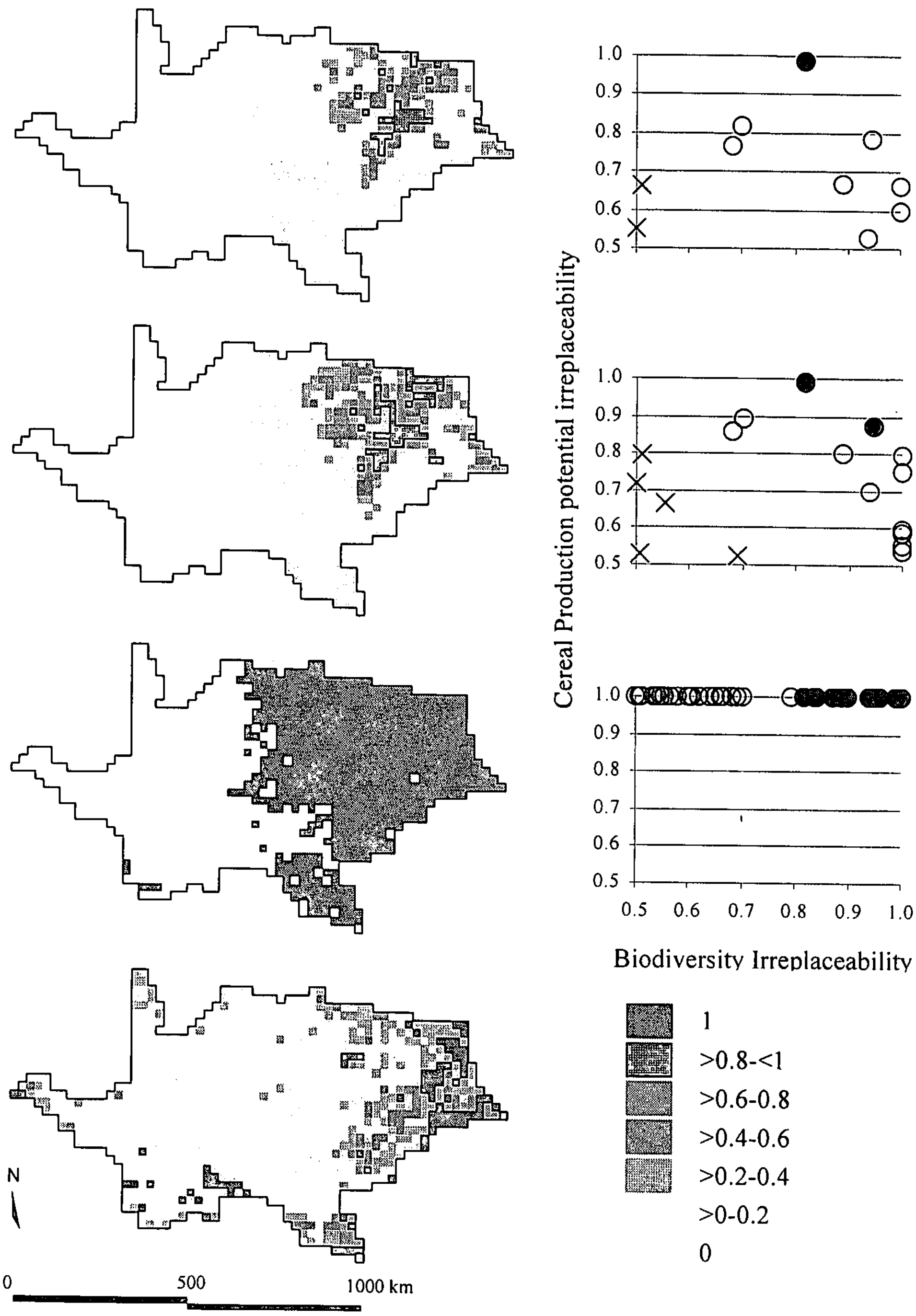

Figure 4. Irreplaceability of sites for cereal production at (a) cereal target 1 (2.779 Mt/yr), (b) target 2 (5.482 Mt/yr) and (c) target 3 (7.261 Mt/yr) and for (d) biodiversity targets. The number of sites with irreplaceability >0.5 for biodiversity targets are plotted against (e) cereal production target 1, (f) target 2, and (g) target 3. Their combined irreplaceability represents the conflict potential between biodiversity and cereal production target achievement. A combined irreplaceability >1.8 indicates high conflict potential (closed circles), >1.4-1.8 indicates moderate conflict potential (open circles) and ≤1.4 indicates low conflict potential (crosses).

The degree of spatial overlap between sites with high biodiversity irreplaceability and high cereal production irreplaceability is high. Of the sites with a biodiversity irreplaceability value of 1, 70.59% of them have some cereal production potential. Of the highly irreplaceable biodiversity sites (irreplaceability between 0.8 and 1), 75% have some cereal production potential, while the sites with low biodiversity irreplaceability (i.e. less than 0.2) only 42.62% have cereal production potential. There are 20 sites that are irreplaceable to biodiversity but that have no cereal production potential. These occur largely in the arid south western Nama Karoo and Succulent Karoo biomes in the very western region of the study area. These low conflict areas are important for biodiversity due to the presence of: Damara Tern (*Sterna balaenarum*), Riverine Rabbit (*Bunolagus monticularis*) and Visagie's golden mole (*Chrysochloris visagiei*). These species obviously create little conflict potential with cereal production potential at a landscape scale. At finer scales, such as a seasonally dry river bed, some conflict may still emerge.

Sites with high conflict potential (high irreplaceability for biodiversity and highly irreplaceability for cereal production potential) increases with increasing cereal production targets (Fig. 4e-g). The percentage of sites with conflict potential (i.e. sites with an irreplaceability above 0.5 for both biodiversity and cereal production potential) increases from 0.9% (low cereal target) to 6.67% (high cereal target). Of these sites, the percentage with high conflict potential also increases from 10% (low cereal target) to 62.16% (high cereal target). The spatial locations of sites with high, moderate and low conflict potential for the three cereal production targets is largely concentrated in the central eastern regions of the basin (Fig. 5). The sites that increase in their conflict potential with increasing cereal production targets lie predominantly on the eastern edge of the study area. At cereal target 1 or 2 there are no biodiversity features that have >50% of their distribution on sites with high conflict potential. But at cereal target 3 there are 40 biodiversity features with >50% of their distribution on high conflict potential sites including: 9 vegetation types, 7 amphibian, 16 bird and 8 mammal species. Five of these species are critically endangered namely the Bittern (*Botaurus stellaris*), Wattled Crane (*Bugeranus carunculatus*), Visagie's Golden Mole (*Chrysospalax villosus*), Blue Swallow (*Hirundo atrocaerulea*), and Rudd's Lark (*Mirafra ruddi*). It is only under cereal target 3, in which all sites with any degree of cereal production potential are irreplaceable, that sites with relatively low cereal production potential in the south eastern arm of the basin are in conflict with those considered important for meeting biodiversity targets.

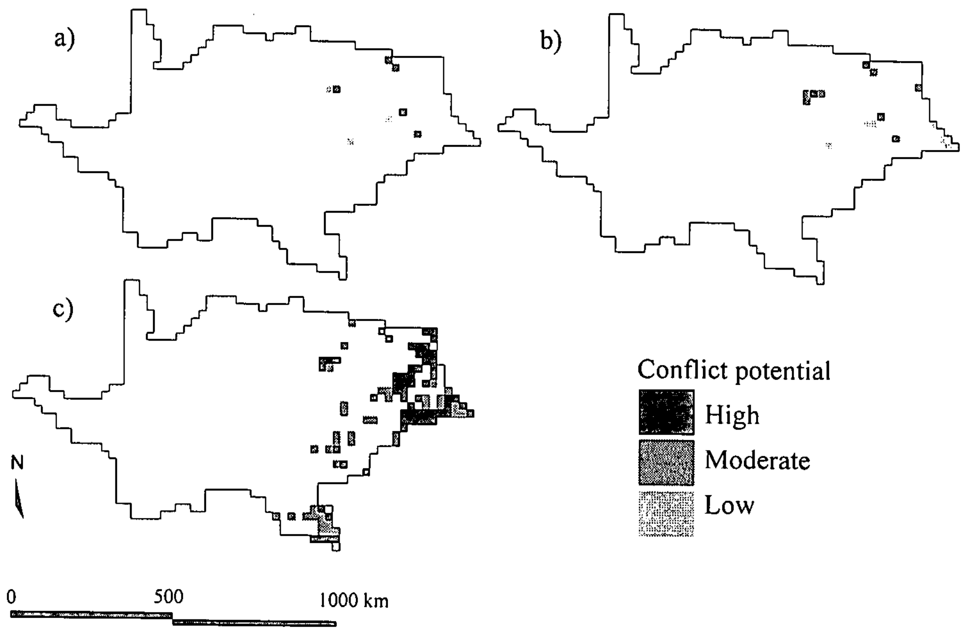

Figure 5. Sites with high, moderate and low conflict potential for achieving both biodiversity targets and cereal production potential targets. Conflict potential is the sum of the irreplaceability value for biodiversity and the irreplaceability value for cereal production. These are calculated for (a) cereal target 1, (b) target 2 and (c) target 3. High conflict potential has a combined irreplaceability >1.8, moderate conflict potential is >1.4-1.8 and low conflict potential is ≤1.4.

Planning scenario comparisons

Considering only the biodiversity irreplaceability of sites, planning scenario 1 selects a set of sites that occupy 19.64% of the study area (Figure 6a). The cost to cereal production potential of this set is 17.68% of the total cereal production potential. As a second step in the iterative heuristic employed, planning scenario 2 takes into account the cereal production potential of a site when breaking ties between sites with the same biodiversity irreplaceability. Planning scenario 2 requires 21.17% of the study area and has a cost of 16.93% to cereal production potential (Figure 6b). Planning scenario 1 requires a smaller area, but with a higher foregone opportunity cost to total cereal production, than planning scenario 2. The decrease in the cost to cereal production potential is small, also when compared to a larger increase in the conservation area required.

Table 3 shows the percentage of sites with high, medium or low conflict potential under cereal targets 1, 2 and 3 that are avoided by the two planning scenarios. Planning scenario 2 avoids a greater percentage of sites with conflict potential than planning scenario 1 at all cereal targets. As seen earlier, the total number of sites with the particular conflict potential (given in brackets in Table 3) increases as the cereal target increases. The percentage of sites with conflict potential that are avoided by each scenario also increases. At cereal target 1, either planning scenario avoids only sites with low conflict potential. Sites with high and moderate conflict potential are sites with high biodiversity irreplaceability that cannot be avoided if biodiversity targets are to be met. The same is true at cereal target 2, although one site with moderate conflict potential is avoided in planning scenario 2. This site has a moderate conflict potential because it has a higher cereal production irreplaceability value (due to the higher cereal target) but it is not essential to achieving conservation targets. During the selection procedure of planning scenario 2, another site with similar biodiversity irreplaceability with a lower cereal production potential was found. The high number of sites with high and moderate conflict potential is attributed to the high number of sites with an irreplaceability value of 1 for cereal production. Of these sites with high conflict potential under cereal target 3, 31.75% are not irreplaceable for achieving biodiversity targets and can thus be avoided. Although a greater percentage of sites with conflict potential are avoided at higher cereal targets, the total number of sites with conflict potential is still higher with higher cereal targets.

The cost to cereal production potential of effective biodiversity conservation incurred in planning scenario 1 and 2 varies across biomes. Biomes were rated from 1 to 7 according to their contribution to total cereal production potential. Table 4 indicates the change in cereal production cost, area and overall change in each biome between the reserve solutions for scenarios 1 and 2. The top 4 biomes all experience a decrease in cost to cereal production potential and an increase in area required in scenario 2. Biomes that have a percentage decrease in cost that is greater than the percentage increase in area are viewed as a good trade-off. Such a situation exists in the Savanna and Thicket biomes. The percentage decrease in the cost to cereal production potential in the Grassland and Nama Karoo biomes is less than the percentage increase in area. These are considered poor trade-offs. The change in the smaller biomes differ, with the Forest biome incurring a decrease in cost to cereal production potential and area, while the Fynbos biome experiences an increases in cost and area in scenario 2. The Succulent Karoo incurs no cost to cereal production potential in scenario 2 but increases in area are required.

Figure 6. Selection of sites to achieve all biodiversity targets (a) based on the irreplaceability of the sites for biodiversity targets alone (planning scenario 1) and (b) based on the irreplaceability of the sites for biodiversity targets and at lowest cost to cereal production potential (planning scenario 2) across the Gariep basin, South Africa.

Table 3. Percentage of sites with conflict potential that are avoided in two reserve planning scenarios. Conflict potential is the combined irreplaceability of a sites biodiversity irreplaceability and cereal production potential irreplaceability at 3 cereal targets: high conflict potential has a combined irreplaceability ≥1.8, moderate conflict potential is ≥1.4-1.8 and low conflict potential is ≥1-1.4. The total number of sites with conflict potential is given in parentheses.

	Planning Scenario 1[a]	*Planning Scenario 2*[b]
Cereal Target 1		
High conflict potential (1)	0	0
Moderate conflict potential (4)	0	0
Low conflict potential (3)	33.33	66.67
Cereal Target 2		
High conflict potential (3)	0	0
Moderate conflict potential (6)	0	16.67
Low conflict potential (6)	66.67	83.33
Cereal Target 3		
High conflict potential (63)	12.70	11.11
Moderate conflict potential (36)	61.11	66.67
Low conflict potential (0)		

[a] *Sites selected using step-wise heuristic based on the highest irreplaceability value to biodiversity targets of the site recalculated after each selection.*

[b] *Sites selected using step-wise heuristic based on the highest irreplaceability value to biodiversity targets and the lowest cereal production potential.*

Table 4. The change in cereal production potential (CPP) and area per biome between the planning scenario 1, in which the opportunity cost for cereal production is not considered during the selection of areas to meet all biodiversity targets, and planning scenario 2, in which the costs to cereal production potential are considered. Symbols refer to the increase (▲) or decrease (▼) in the cost to CPP or area between the two planning scenarios. The = sign indicates no change in the CPP cost or area between scenarios.

Biome	*Total CPP rank*	*Change in cost*	*% change in cost*	*Change in area*	*% change in area*	*Change result*
Grassland	1	▼	-0.11	▲	1.94	Poor
Savanna	2	▼	-1.04	▲	0.13	Good
Thicket	3	▼	-10.42	▲	3.22	Good
Nama Karoo	4	▼	-1.37	▲	1.96	Poor
Forest	5	▼	-7.24	▼	-8.41	Good
Fynbos	6	▲	9.80	▲	9.37	Poor
Succulent Karoo	7	=	0.00	▲	1.18	Poor

DISCUSSION

The distribution of cereal production potential, which decreases from east to west across the Gariep basin, is partly a function of the region's precipitation pattern, which follows the same trend. Linked to this, and also influential, is the decrease in area converted to agriculture from east to west. Thus, high levels of cereal production potential are concentrated in the eastern areas of the Gariep basin, in an area commonly referred to as the "bread basket" of southern Africa (Bohensky et al. 2004). Currently, sufficient calories are produced in the Gariep basin to meet the minimum nutritional demands of its population. Indeed, national domestic production meets approximately 90 percent of South Africa's food consumption demands (Kamara and Sally 2002; Bohensky et al. 2004). It is suggested that the Southern African Development Community (SADC) region, of which the Gariep is a part, as a whole has the potential to meet the food needs of the population both now and in the future if political, economic and technological constraints can be overcome (Scholes and Biggs 2004). As limited extensification of cultivated lands is anticipated, future production demands will largely be met through an intensification of agriculture on already cultivated lands (Scholes et al. 1999). This has implications for the environment, as the increase in cereal production per unit area can place greater pressure on biodiversity and ecosystems through detrimental trade-offs related to excessive water consumption or fertilizer and pesticide use (Bohensky et al. 2004; MA 2005). Sustainable practices and technological developments are required to prevent, assess and reverse such impacts. But ultimately, sufficiency of food resources does not equate to food security (Biggs et al. 2004; Bohensky et al. 2004). With only half of South Africa's crop production used for domestic consumption and the remainder used as livestock feed or exported, the generally self sufficient Gariep basin holds millions of people for whom food insecurity at a household level is a reality (Bohensky et al. 2004; HSRC 2004). Such complexities further exemplify the inherent difficulty in estimating cereal demands and mapping cereal production supply and demand surfaces.

The application of irreplaceability to cereal production potential succeeds in making the value of sites for cereal production targets comparable to the values for meeting conservation targets, highlighting where areas of high irreplaceability for both objectives overlap. For cereal production potential, the calculation of the irreplaceability of sites only considers a single feature. The irreplaceability surfaces thus mirror the distribution of cereal production potential, with sites with higher cereal production potential having higher irreplaceability values as they contribute relatively more towards achieving cereal production targets. Although this means that in this case we may simply have been able to use the actual cereal production potential surface, irreplaceability can be applied to more than one cereal type once appropriate data becomes available. In that case, irreplaceability will be able to indicate more than just 'richness' (i.e. production potential) but it will also pick up areas that are important for a range restricted cereal (e.g a cereal type that only grows in a few areas). Although the model of cereal production potential and cereal targets set are not ideal, as the data required to make them more accurate was not available, they do provide a good indication of the spatial distribution of potential production areas and are useful in this assessment of potential land-use conflict.

Increasing cereal targets lead to more sites with higher irreplaceability values, indicating that with increasing cereal demands due to increasing human population and per capita consumption patterns, the importance of sites with high cereal production potential for meeting these demands will increase. Higher irreplaceability values for cereal production potential lead to a higher potential for conflict with and pressure on biodiversity, particularly in the eastern regions. Even at low and moderate cereal production targets, areas of potential conflict between biodiversity and cereal production are evident in the eastern Gariep. While there are fewer than twenty sites with conflict potential at low to moderate cereal production targets, it is likely that these areas are already highly threatened by existing cultivation patterns, and efforts to conserve the important biodiversity features found there will be crucial. With low and moderate cereal production targets, sites with high conflict potential have high biodiversity irreplaceability as they are crucial for achieving the Dry Clay Highveld grasslands, Bittern and Wattled Crane biodiversity targets. The number of sites with conflict potential increases with a high cereal production target, where the potential of the basin to produce sufficient cereal becomes stretched and marginal production lands become important for contributing towards the cereal production needs of the population. The number of biodiversity features under potential threat also increases, with 9 vegetation types and 31 species (5 of them critically endangered) added to the list of features in jeopardy. Most of these vegetation types are grasslands and many of the species affected are grassland dwelling, or at least partly so. The threatened conservation status of grasslands is largely driven by the conversion of land to agriculture and urbanization, has been emphasized previously and is becoming the focus of conservation planning efforts in the biome (Jansen et al. 1999; Bohensky et al. 2004).

Conservation plans that seeks to avoid areas of high cereal production potential that are not crucial to achieving conservation targets would go a long way towards finding efficient and feasible conservation solutions, which have a higher chance of being implemented quickly. Equally, areas important to conservation goals that cannot be avoided and have high cereal production potential would require high prioritisation for finer scale planning and conservation action. It is expected that any algorithm that minimizes costs during the selection process would lessen the overall cost of a reserve selection, but at the expense of area efficiency (Faith 2001a, b; Pressey et al. 2004). While decreases in area efficiency are expected, the relative trade-off between the cereal production costs minimized and the increase in area required should be considered, in that some biomes demonstrate decreases in cereal production that may not be considered a favorable trade-off when compared to the increase in the conservation area required. This is especially so when taking into account the costs associated with increased land purchases, land management and opportunity cost to alternative land uses. It is not surprising however that the use of the simple heuristic algorithm applied in this study, which breaks ties between sites with equal irreplaceability values for biodiversity by selecting the site with the lowest cereal production potential, did not find a particularly improved solution. The problem of maximizing biodiversity representation, minimizing cereal production potential costs and maintaining area efficiency is complex and finding better solutions to such problems would be benefited by more complex algorithms. Thus while C-Plan is useful for calculating irreplaceability, conservation planners will have to master other conservation planning software tools if more complex planning problems are to be explored. However, we propose that irreplaceability provides a valuable unit free ratio of comparison between different sectors that highlights areas of high irreplaceability for both objectives, which will be difficult to completely avoid irrespective of the conservation planning approach adopted.

Implications for conservation in the Gariep basin

The need for integrated research and planning at all scales is crucial, especially in the eastern areas of the Gariep basin where the conflict potential is high. This analysis provides only a broad scale assessment at a coarse resolution, but an important measure in avoiding trade-offs in biodiversity objectives and cereal production will be the search for conservation solutions at a finer resolution. Finer scale planning that refines the needs and opportunity costs involved in preserving biodiversity in areas of conflict could make a substantial contribution to avoiding or deciding upon trade-offs in the Gariep basin. Although with increasing cereal demands and associated conflict potential, finding solutions that avoid trade-offs will become more difficult, even with fine scale planning.

The best approaches to conserving biodiversity in agricultural landscapes still need to be investigated further. Agricultural land could have significant potential for conserving certain biodiversity patterns and processes (Daily et al. 1998; Daily 1999; Conway and Toenniessen 2003; Van Buskirk & Willi 2004; Green et al. 2005). One approach to conserving biodiversity is through the partial protection of biodiversity inside agricultural landscapes, which increases the density of biodiversity features on cultivated land at the possible expense of agricultural yields (Faith 2001b; Faith & Walker 2002). Green et al. (2005) investigated the persistence of species in such wildlife-friendly agricultural practices, compared to land sparing agricultural practice, which advocates the intensification of yield production per unit area in already converted lands and thus limits the demand for farmland. Although solutions depend on the production targets considered, and importantly on the frequency of species that have different density-yield functions, their study suggests that high-yield (land sparing) farming may allow more species to persist. If this applies to the Gariep basin, it would influence how trade-off decisions are made. Decisions regarding trade offs involved in conserving biodiversity and producing sufficient cereal and the success of such decisions are likely to be more complicated in areas such as the Gariep basin where although the region appears to produce enough food, food insecurity is still a reality. Priorities of the government and many millions of people in the Gariep still sit with food production and less with biodiversity conservation. It is likely that a range of conservation approaches and integrated responses will best serve effective conservation in the Gariep basin (Moore et al. 2004; Faith & McNeely 2005). Further research is required to investigate the relationship between biodiversity and productivity, as well as the social, economic and ecological implications of possible trade off decisions. The gaps in our knowledge regarding species benefits from different agricultural practices and management, the intensity of agricultural activities (Wickramasinghe et al. 2004), and the amount of land that needs to be set-aside to see increases in species abundance and diversity (Van Buskirk & Willi 2004) should form the basis of focused research (Cowling et al. 1999; also see Green *et al.* 2005).

The inclusion of factors which greatly influence the distribution of biodiversity features and pressures on biodiversity, and which will significantly impact the future success of conservation plans developed today, is also essential. If future changes are not taken into account soon, the success of finer scale planning to avoid conflict and aid in making trade-offs will be compromised. Both biological diversity and maize production have high vulnerability to climate change in South Africa (van Jaarsveld & Chown 2001; DEAT 2003; DEAT 2004). Biodiversity losses are predicted to be largest in the western, central and northern regions of South Africa as patterns of species range shifts eastwards towards the eastern highlands, while the western parts of the country are predicted to increase in aridity (van Jaarsveld & Chown 2001, DEAT 2003). At the same time, net revenue from field crops in some areas is predicted to increase (Gbetibouo & Hasson 2004), leading to higher conflict potential with biodiversity in different areas in the future. Despite the increase in some areas, a decrease in overall maize production of approximately 10 - 20% over the next 50 years is predicted (DEAT 2003). This will also place added pressure on land with cereal production potential. Adaptation measures to such impacts require measures to buffer the effects of climate change through integrated and innovative management and planning (South Africa's likely adaptation measures are detailed in DEAT 2003). Although few conservation plans have done this so far (but see Williams et al. 2005), it is inevitable that effective conservation solutions that aim to ensure the persistence of biodiversity features will require the incorporation of climate change considerations (Rutherford et al. 1999; Hannah et al. 2002).

Focused and applied research and finer scale planning will be also be aided by more realistic and predictive models of cereal production potential, as well as by supportive, effective and well implemented policies. Implications of the exclusion of exports and imports in the estimation of cereal targets used in this study are that the cereal targets likely to underestimate the demand for cereal, as the region is an important exporter. Thus, the large number of sites with high conflict potential at high cereal targets is probably indicative of regions that require focused assessment now. Overall, the need for improved measures of biodiversity, and prediction of the direct and indirect drivers of change in biodiversity and ecosystems in order to aid decision-making at all levels, was highlighted in the Millennium Ecosystem Assessment (MA 2005). This need has also been identified at a national level (Neke & Du Plessis 2004; Bohensky et al. 2004; Driver et al.

2005). More accurate models of cereal production supply and demand will aid biodiversity conservation as well as benefiting agricultural planning in the face of future changes. Policies that enforce the application and development of tools and technologies that can be applied on a sufficient scale to limit the negative impact of agricultural practices on ecosystems and encourage sustainability are also required (MA 2005). There has been an encouraging move towards such legislation in South Africa, as mandated by the South African constitution (South African Government 1996; NDA 1998; NDA 2001; Donaldson et al. 2003), but adherence to legislation and environmental guidelines becomes essential to conservation success as well as the provision of important ecosystem services and cereal production (Balvanera et al. 2001, Pressey et al. 2003; Wessels et al. 2003).

CONCLUSION

Some studies indicate that focusing conservation efforts on land with the least extractive value, or with lowest acquisition or management costs, is not always beneficial to achieving conservation objectives over the long term (Mier et al. 2004, Moore et al. 2004; Pressey et al. 2004). However, the integration of opportunity costs and various socioeconomic considerations into systematic conservation planning will likely provide better and more practical solutions at the current stage of national development and conservation need, than focusing exclusively on refining biological selection criteria (Moore et al. 2004). The application of irreplaceability to biodiversity and cereal production potential provides a means of comparing the importance of an area to these different sectors and evaluating a region's capacity to meet diverse demands. It highlights areas of high irreplaceability to both objectives where there is high potential for conflict, where trade-offs are likely, and which may require prioritization for conservation action. The irreplaceability approach used has the potential to be expanded and to incorporate more than one opportunity cost.

Assessments that continue to evaluate these dynamics and the associated trade-offs are essential. The value of this approach is in identifying trade off areas and making the potential for conflict spatially explicit, which is useful for conservation planners when engaging with different sectors. More complex area selection approaches, which will likely require more technical expertise to use, are required to find optimal solutions in such situations. But frequently, areas with high conflict potential will be difficult to avoid irrespective of the area selection techniques employed and the location of areas with potential for conflict early on could be crucial. Trade-offs between competing objectives within a dynamic and hungry world are inevitable and it is suggested that if action is not taken now, targets for poverty reduction and reduction in biodiversity loss will not be met within their allotted timeframes (MA 2005). The future success of biodiversity conservation and sustainable agricultural ventures is reliant on the measurement of biodiversity and ecosystem services, our understanding of the relationship between these and the maintenance of human well-being, and on our ability to plan for both in an integrated manner. Approaches that facilitate the evaluation of trade-offs, promote negotiation and present solutions towards more cost effective and socially acceptable solutions, will serve to strengthen the partnership between conservation and civil society (Nagendra 2001; Balvanera et al. 2001; Postel 2003; Faith & McNeely 2005).

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CHAPTER 3

Multi-objective conservation planning: Conserving biodiversity while ensuring cereal production using a simulated annealing algorithm

ABSTRACT

This chapter explores the use of simulated annealing, a global heuristic algorithm available in the conservation planning software platform MARXAN, to investigate reserve solutions that minimize the cost to cereal production potential while maximizing representation of conservation feature targets in the Gariep basin, South Africa. An objective function, in which penalties associated with a number of parameters are set, is used to evaluate reserve solutions. Three planning parameters that affect the penalty on the objective function are investigated: the conservation feature penalty factor; the cost threshold; and the cost threshold control parameter. Results indicate an important trade-off between penalties. The penalty for not achieving all conservation feature targets is traded off against exceeding the cereal cost thresholds, sometimes at the expense of conservation features. When the achievement of conservation targets is not negotiable it is the spatial distribution of reserve solutions that is. Simulated annealing generates numerous good solutions to a conservation problem described by an objective function. The frequency with which individual sites are selected across this range of solutions indicates the utility of individual sites for achieving the objective function. This is an important measure of flexibility in planning. Overall the approach finds good solutions in a manner providing both flexibility and efficiency. Most variability between solutions is in the central eastern region of the basin where both cereal production potential and biodiversity feature richness are high. Some trade-offs amongst these sites are unavoidable. The advantage gained is that the results make explicit what is lost or gained through the respective choices made (the trade-offs). Two unexpected outcomes emerged from the analysis. First, simply the application of the cost threshold function influenced the solutions generated. Objective functions with cost thresholds high enough that any reserve solution generated to meet biodiversity targets would not exceed it still had higher cereal production potential costs than solutions generated for objective functions for which no cost threshold was applied. The application of the cost threshold function therefore influences reserve solutions regardless of the cost threshold used. Second, objective functions with low cost threshold values for which it would be expected that the costs to cereal production potential would be minimized, had higher cereal production potential costs than the solutions generated for objective functions where easily achievable (high) cost thresholds were applied. The cost threshold function can thus limit the ability of the objective function to find optimal solutions. These outcomes indicate that the sensitivity of reserve solutions to these planning parameters still requires some further exploration, particularly with reference to setting the most appropriate cost thresholds and control parameters.

INTRODUCTION

Systematic conservation planning provides a framework for the effective conservation of biodiversity. The principles and advantages of systematic conservation planning have been well documented by scientists and practitioners across the world (for reviews see Ferrier et al. 2000; Margules & Pressey 2000; van Jaarsveld et al. 2003) and have over the past 20 years set it apart from other forms of planning. These principles include the quantitative setting of targets for spatially explicit biodiversity features, and the principles of complementarity, representivity and persistence (Pressey et al. 1993; Margules & Pressey 2000). The goal of conservation planning is the selection of areas that will efficiently and effectively represent all quantitative biodiversity features, at minimum cost, in terms of land area, management costs or opportunity costs to other land uses (Pressey et al. 1996; Margules & Pressey 2000; Faith & Walker 2002; Margules et al. 2002; Moore et al. 2004). The problem is usually addressed mathematically using algorithms run on conservation planning software platforms. Over the past two decades these software platforms have become invaluable tools to conservation planners and decision makers.

A large variety of conservation planning software platforms exist. They are based on different algorithmic approaches to solving conservation area selection problems (Moore et al. 2003; Pressey 2003). These approaches include optimization methods, heuristic approaches and methods using multivariate spaces (Pressey 2003). A number of studies have investigated their respective benefits and limitations, in terms of the data they use, the analyses they include, outputs they provide, their usability in interactive negotiations, and their ability to consider multiple objectives. Although optimisation algorithms are very powerful and capable of considering multiple objectives simultaneously, traditionally they have not been frequently used. This was as they were often prohibitively time consuming (but see Rodrigues & Gaston 2002), required investment in resources and expertise, and failed when problems were non-linear (Moore et al. 2003). These constraints are decreasing as computers get faster and better software becomes available. Heuristic algorithms, although unable to guarantee optimal solutions, are more frequently utilized in conservation planning and have generally compared favourably with optimal solutions (Moore et al. 2003). Heuristic algorithms can be divided into global heuristics, largely developed by operations researchers, and local heuristics largely developed by conservation researchers (Moore et al. 2003; Pressey 2003). Local heuristic algorithms have proved most popular in the conservation planning arena (Balmford 2003), despite being unable to guarantee an optimal or quantitative solution and sometimes being outperformed by alternative algorithms (Pressey & Nichols 1989; Pressey et al. 1996; Pressey et al. 1997; McDonnell et al. 2002). On the whole these algorithms are efficient, manageable, and provide relatively robust, rapid and reasonable answers that are easily communicable (Pressey et al. 1997; Possingham et al. 2000; Moore et al. 2003). These algorithms use a list of rules to select areas iteratively and most are based on the principle of complementarity, which adds areas to maximize the number of new biodiversity features in a stepwise fashion (Sarkar and Margules 2002). Constraints, other than the number of sites selected are considered as secondary factors when solving ties during the area selection process. Global heuristic algorithms include simulated annealing, neural networks and genetic algorithms. These algorithms work on the selection of sets of areas, can simultaneously consider multiple constraints, and provide a useful quantitative estimate of the quality of their solutions (provided by an objective function score in simulated annealing). They have a long history outside of conservation planning applications and their performance and limitations have been well studied and defined (Rothley 1999; Rodrigues et al. 2000; Moore et al. 2003).

Conservation planning and opportunity costs

The incorporation of alternative land uses in conservation planning has largely been in the form of threat assessments to biodiversity persistence (Williams & Araujo 2000; Gaston et al. 2002) and for prioritizing conservation areas in need of immediate conservation implementation (Pressey & Taffs 2001; Reyers 2004). Attempts to minimize the impact of reserve selection on alternative land uses have also largely been limited to ensuring area efficiency in conservation area selection, first described by Kirkpatrick (1983) as a minimum-representation problem. Fewer studies have directly incorporated the opportunity costs associated with other forms of land use into conservation assessments. Opportunity costs are defined as the forgone cost of choosing one land use in favour of another (Faith & Walker 2002). This is despite many of these competing land uses being of direct importance to human well-being, local and regional economies and development (Bohensky et al. 2004).

There is at least some degree of spatial overlap between areas considered of biological, social and economic importance in South Africa (Fairbanks et al. 2000; Reyers et al. 2000; Chown et al. 2003; Wessels et al. 2003; Bohensky et al. 2004; van Rensburg et al. 2004), and in other parts of the world (Balmford et al. 2001, 2003). Given the realities of limited conservation resources and competing demands for land use, it would be beneficial if area selection techniques strived to minimise overlap with areas important to other land use sectors while continuing to represent relevant biodiversity features. The need for integrative frameworks that provide practical, defensible recommendations towards regional natural resource and land use planning is increasingly recognised by governments and planning authorities as a more appropriate approach (Kremen et al. 1999; Balvanera et al. 2001; Pressey 2003; Bohensky et al. 2004; Faith & McNeely 2005). Regional-scale plans that seek to optimise the potential net benefits of a region to society by simultaneously considering biodiversity conservation and human well-being requirements hold the key to better solutions to all stakeholders (Gelderblom et al. 2002; Balmford 2003; Cowling and Pressey 2003; Faith & McNeely 2005).

A variety of approaches have been used to incorporate opportunity costs into conservation area selection procedures. Approaches that make use of iterative heuristics, includes an approach that iteratively selects areas from random starts ensuring that the complementarity value of the site selected exceed the weighted opportunity costs of the site. This approach, which is used by the TARGET module in the DIVERSITY software package (Faith & Walker 1994, 1996), proved effective in minimizing the opportunity costs to the timber industry in Papua New Guinea (Faith 2001b; Faith et al. 2001a, 2001b). Other approaches based on the iterative selection of sets of areas include those that select areas with the highest ratio of complementarity to foregone opportunity cost (Balmford et al. 2001 using WORLDMAP – Williams et al. 1996) or those that iteratively select areas of maximum conservation value and minimum opportunity costs (Wessels et al. 2003 using C-Plan - NSW 1999; Roberts et al. 2003a, b). Approaches that use optimisation algorithms to select areas make use of an objective function that provides a score for a set of sites as if that set constituted a single conservation area. The objective function provides a score based on the costs and penalties incurred by the set of sites and indicates how good the solution is in comparison to other sets of sites. Because an objective function can include a variety of penalties, they can simultaneously considered opportunity costs with biodiversity objectives to select truly optimal (Moore 2001 using C-plex – ILOG 1997-2000) or near-optimal solutions (using simulated annealing algorithms using MARXAN – Ball & Possingham 2000). The use of simulated annealing in conservation planning software called MARXAN provides a relatively new and flexible optimization tool (Ardron et al. 2002; Leslie et al. 2003) that performs well compared with alternative heuristic algorithms (Possingham et al. 2000; Stewart et al. 2003). The ability of these algorithms to find good solutions has been illustrated previously (Day et al. 2002; McDonnell et al. 2002) and has proved influential in the Australian marine conservation planning arena (Day et al. 2002; see Ecological Applications Supplement issue 2003).

This paper evaluates the ability to efficiently conserve biodiversity in the face of increasing human demand for cereal production across the Gariep basin in South Africa. The need to feed a growing human population is one of the oldest land use activities and one of the greatest drivers of habitat transformation (MA 2005). The challenge of securing cereal production potential and biodiversity across one of the Southern African Millennium Ecosystem Assessment's (SAfMA - Biggs et al. 2004) regional study areas (Bohensky et al. 2005), provides an ideal opportunity to test the value of using simulated annealing for land use trade off assessments in a terrestrial environment.

Objective function

An objective function calculates a quantitative score for a combination of sites. This allows for combinations of sites that form possible reserve systems to be compared with each other or for changes in a combination of sites to be compared in order to establish whether the change was good or bad. A low objective function score represents a better reserve solution. An objective function score, C(x), is determined by the cost of the sites selected and a penalty for any biodiversity features are under-represented. Additional penalties on the objective function may include penalties if the cost of the sites selected exceeds a certain threshold, or if certain spatial fragmentation criteria are not achieved. A penalty increases the value of the objective function. This process can be summarised as follows:

$$C(x) = \sum_{Sites} \text{Cost} + \text{BLM} \sum_{Sites} \text{Boundary} + \sum_{ConValue} \text{CFPF x Penalty} + \text{Cost Threshold Penalty (t)} \qquad \text{(Eq. 1)}$$

Here, the cost is the sum of a cost measure, in terms of the area, economic cost or opportunity cost for other land uses, for each of the sites within a selected reserve system. The constant, BLM, is the boundary length multiplier, which converts the reserve system cost and its boundary length (being the length (or possibly cost) that the sites in a planning solution share with unprotected units) into a common currency and determines the importance placed on minimising the boundary length relative to minimising cost (Leslie et al. 2003; Stewart et al. 2003). A boundary length multiplier of 0 excludes the boundary length from the objective function, thus placing no penalty on highly fragmented reserve solutions. A boundary length multiplier higher than 0 increases the degree of connectivity and clumping required between selected sites (Ball & Possingham 2000; Possingham et al. 2000; Leslie et al. 2003; Stewart et al. 2003).

Summed for all conservation features, the next component of the objective function inflicts a penalty if conservation features are not adequately represented. CFPF is the conservation feature penalty factor. It is a weighting factor that determines the relative importance of effectively reserving any particular conservation feature (Ball & Possingham 2000). Certain conservation features, such as critically endangered species, can be assigned high conservation feature penalty factors to ensure that they are incorporated (McDonnell et al. 2002; Stewart et al. 2003). There is no standard approach for determining the conservation feature penalty factor. The overall penalty for conservation features that are underrepresented is the sum of the conservation feature penalty factor of each underrepresented feature multiplied by the total cost of the set of sites needed to adequately reserve the conservation features that are not presently adequately represented in the reserve solution (Ball & Possingham 2000). Conservation feature penalty factors much greater than 1 are more likely to guarantee representation of conservation features to the specified target (Ball & Possingham 2000) and Ardron et al. (2002) also suggest that this penalty should vary to be proportional with the cost threshold penalty.

The cost threshold penalty is an optional penalty applied if a cost threshold determined for the total suite of selected sites is exceeded. This penalty is a function of the cost of the reserve system, depends on the algorithm used to select sites and will change as the algorithm progresses (Ball & Possingham 2000). Using a simulated annealing algorithm, the objective function is penalized whenever the sum of the cost measure increases above the specified cost threshold value. The cost threshold penalty value depends upon the degree to which the cost threshold has been exceeded and is determined by two cost threshold control parameters as follows:

$$\text{Cost Threshold Penalty} = \text{Amount over Threshold} \times (Ae^{Bt} - A) \qquad \text{(Eq. 2)}$$

where t is the proportion of the run (from 0 to 1), A controls the final value and B controls how steep the curve is (Ball & Possingham 2000). These two control parameters can be set to penalize any threshold excesses more or less strictly, depending on user needs.

Different optimization methods can be used to select sets of sites. This study focuses on the use of simulated annealing to select sets of areas as potential reserve solutions for the Gariep basin.

Simulated annealing

Simulated annealing is an optimisation algorithm used in conservation planning software to select sets of sites as part of a potential reserve system. Selections are given a score based on the objective function and changes to the sites selected are compared and accepted based on the calculated objective function score and the stage of the simulated annealing process.

To begin with a random set of sites is selected (the size can be predetermined and varies from 0 to all of the available sites). The algorithm then proceeds through three stages (Figure 1):

1) Iterative improvement – the addition or deletion of sites that decrease (improve) the value of the objective function.
2) Random backward steps – avoids local minima, in the search for the global minima, by allowing the addition or deletion of sites that increase the value of the objective function (dependent on the annealing schedule and acceptance function set).
    a. The application of an additional algorithm to refine the selection is applied at the end of this process.

3) Repetition of the random selection of sites, iterative improvement and annealing. A greater number of repetitions will increase the chance of finding an optimal solution.

Simulated annealing differs from other iterative approaches in that random sets of areas are selected early on in the process, allowing the algorithm to choose less than optimal sets initially. This initial random selection in combination with the stochastic addition or deletion of sites that do not necessarily improve the value of the objective function (stage 2), provide numerous solutions to a single problem, which may lead to better solutions later as the algorithm becomes more stringent (Ardron et al. 2002). The probability of 'poor choices', defined as the inclusion or exclusion of a site that increases the value of the objective function, being accepted is determined by the annealing schedule (Ball & Possingham 2000; McDonnell et al. 2002).

The annealing schedule is analogous to the physical process of heating and cooling metals to obtain a strong crystalline structure. It is determined by the setting of the acceptance function parameters, such as the initial temperature, number of temperature decreases and final temperature. Determination of a good annealing schedule requires great care and patience, as only a number of 'rules of thumb' exist for its determination (Kirkpatrick 1983; Kirkpatrick et al. 1983; Lundy & Mees 1986; McDonnell et al. 2002). The annealing schedule can be fixed (determined by the user) or adaptive (determined by the algorithm) (Ball & Possingham 2000). Using a fixed annealing schedule generally produces better results more quickly than an adaptive annealing schedule (Ball & Possingham 2000; Ardron et al. 2002). A fixed annealing schedule was therefore used in this study and is explained in more detail.

The algorithm completes a user-defined number of iterations (at each iteration a site is randomly included or excluded) (Ball & Possingham 2000). The more iterations the better the chances are of finding a good solution. The acceptance function determines the duration of this time during which poor choices are accepted (stage 2). The initial temperature starts high and decreases with each iteration. Figure 1 illustrates schematically that while the temperature is high, 'poor choices' have a higher probability of being accepted, but as the temperature decreases, the chance that a 'poor choice' is accepted decreases. The amount of time the algorithm spends at high or low temperatures is based on the rate of temperature decrease. If the temperature decreases quickly the algorithm may not have enough time at high temperatures to find good selections and spend too much time at low temperatures refining that selection. If the temperature decreases slowly the algorithm may not spend enough time at lower temperatures refining the selection of sites. It is at the point when the temperature is lowest and only good choices are accepted that other algorithms, such as a summed irreplaceability heuristic, can be used in combination with simulated annealing to refine the selection (Ball & Possingham 2000). The summed irreplaceability heuristic acts to reduce redundancy by determining how essential each site is for achieving conservation targets for each feature and improves the final reserve solution by ensuring that both rarity and richness are incorporated (Ardron et al. 2002). Another algorithm, recommended follow-up algorithm to simulated annealing, is normal iterative improvement, which checks the utility of each site in the final design and ensures that the final set of sites is a local minima (Ball & Possingham 2000; Ardron et al. 2002).

The final element of simulated annealing is that the algorithm repeats this process in each run. The user determines the number of runs and the best solution is determined based on the lowest objective function score. Table 1 provides a list of the technical terms related to the objective function and simulated annealing described in these sections.

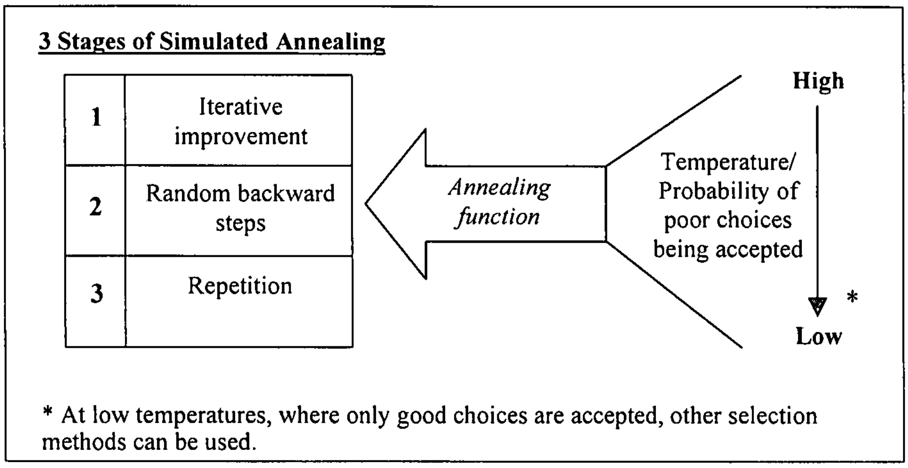

Figure 1. Schematic diagram of the three steps of simulated annealing, and the annealing function that drives the acceptance and rejection of sites.

Table 1. Description of technical terms related to the objective function and simulated annealing in the conservation planning software platform MARXAN.

Term	*Description*
Objective function	A score given to any set of sites depending upon how good the combination of sites performs as a reserve system. Defines what is desired in a reserve system without explicitly defining how an optimal reserve will be found.
Simulated annealing	Optimisation algorithm that selects sets of sites based on an annealing schedule.
Cost	Sum of the cost of a set of sites – area, economic cost or opportunity cost
BLM	Boundary length modifier - converts the reserve system cost and its boundary length into a common currency and determines the importance placed on minimising the boundary length relative to minimising costs.
Boundary	Boundary length (or some other cost) of sites shared with unselected sites.
CFPF	Given to each conservation feature, the conservation feature penalty factor determines the relative importance of effectively reserving a particular conservation feature.
CFPF Penalty	Cost of the planning units required to adequately represent a conservation feature if it is not adequately represented.
Cost threshold	Threshold related to the total cost of the sites – represents a total area, economic or opportunity cost that must not be exceeded.
Cost threshold penalty	Optional penalty applied if a cost threshold is exceeded. It is a function of the cost of the reserve system and the cost threshold control parameters.
Cost threshold control parameters	Two parameters that control how quickly the set of sites is penalised once the cost threshold has been exceeded.
Annealing schedule	Determines the probability of additions or deletions of sites being accepted over the iterations run. Is crucial for the performance of the simulated algorithm

Aims and objectives

The additional and optional capabilities of MARXAN in considering a number of spatial parameters through the objective function and for setting various types of targets, such as the boundary length multiplier, the spatial aggregation rule (minimum clump size or minimum viable population size) and spatial separation rule (specifies distance that separates clumps or sites that contain a particular conservation feature) have proved useful in the design of reserve solutions. Studies that have applied simulated annealing using this conservation planning software have focused largely on the software's ability to consider these spatial relationships and constraints (Possingham et al. 2000; McDonnell et al. 2002; Airame et al. 2003; Leslie et al. 2003; Stewart et al. 2003). Few studies to date have tested the implications of setting different conservation feature penalty factors, cost thresholds or cost threshold penalties on the objective function score and final generated reserve solutions. This chapter explores the use of simulated annealing, in MARXAN, to investigate reserve solutions that minimize the opportunity cost to cereal production potential while maximizing the representation of biodiversity features. The sensitivity to and variation of final reserve solutions with different conservation feature penalty factors, cost thresholds and cost threshold penalties are assessed. These parameters have significant implications for reserve solutions. The aims of this study are therefore twofold, first to incorporate the opportunity costs for cereal production potential into the biodiversity conservation planning problem, secondly to test the application of simulated annealing to this reserve problem and show the variation caused by alterations in the conservation feature penalty factors, cost threshold set and cost threshold penalties. In thus doing, different reserve solutions can be identified and areas of conflict and trade-off investigated.

METHODS

Study Area

The Gariep basin has an area of 683,600km^2 incorporating the whole of Lesotho and 60.7% of central South Africa (Fig. 1). The basin formed a component of the sub-global Southern African Millennium Ecosystem Assessment (SAfMA – Biggs et al. 2004), which is part of the global multiple-scale Millennium Ecosystem Assessment (MA 2005). The basin comprises the Senqu-Gariep-Vaal river system, and two primary catchments connected to the system by major water transfer schemes: the Tugela in KwaZulu-Natal Province and the Great Fish in the Eastern Cape Province. The region is marked by a distinctive west-east precipitation gradient, contains all 7 of South Africa's biomes (Low & Rebelo 1996), but is predominantly made up of the Savanna, Grasslands and Nama Karoo biomes. The Savanna biome is the smallest of these but is the most speciose, containing a fair number of endemic and endangered species. The Grasslands biome contains the most endemic and endangered species, with the Drakensberg grasslands being a recognised center of endemism. The biome is however heavily transformed and poorly protected (Fairbanks et al. 2000; Reyers et al. 2001). The Nama Karoo is the largest biome but least speciose. Although this biome contains substantial numbers of the region's endemic and endangered species, this semi-arid biome is least protected (Reyers et al. 2001). Important human pressures in the basin include agriculture, urbanisation, industrial and mining developments, grazing, afforestation, invasion alien species and the alteration of water flow regimes and water quality (Bohensky et al. 2004). The Gariep basin study area was divided into 1110 quarter-degree square (QDS) grid cells (15' x 15' ~ 700km^2; hereafter referred to as a site) (Fig. 1). All data were generalised to a common resolution of a QDS to conform to the coarsest resolution of the species distribution data.

<u>*Data*</u>

Biodiversity features and targets

Biodiversity feature data included distribution data on amphibians, birds, mammals and vegetation types. The Gariep basin holds 40 vegetation types - defined as having "similar vegetation structure, sharing important plant species, and having similar ecological processes" (Low & Rebelo 1996). Species distribution data were collated from the Southern African Frog Atlas Project (Minter et al. 2003), the Southern African Bird Atlas Project (Harrison et al. 1997) and mammal distribution data (Freitag & van Jaarsveld 1995, Keith 2004). These databases were considered of suitable spatial resolution, taxonomic completeness, and with limited bias over the national geographic extent (Rouget et al. 2004). Only those species categorized as "species of special concern" (Rouget et al. 2004) being species either endemic to the region or threatened, according to the IUCN classifications of Critically Endangered (CR), Endangered (EN), Vulnerable (VU) and Near Threatened (NT) (IUCN 2001), were included. Marine, vagrant and exotic species were excluded from the analysis. This is in line with national conservation plans and assessments in South Africa (Rouget et al. 2004). In total, there were 10 amphibian (2 endemic, 0 CR), 63 bird (0 endemic, 4 CR species) and 21 mammal (3 endemic, 3 CR) species included in the analysis. Distribution data on vegetation types were collated from Low and Rebelo (1996). Biodiversity features with more than 95% of their distribution falling outside of the basin were considered marginal and excluded from the analysis.

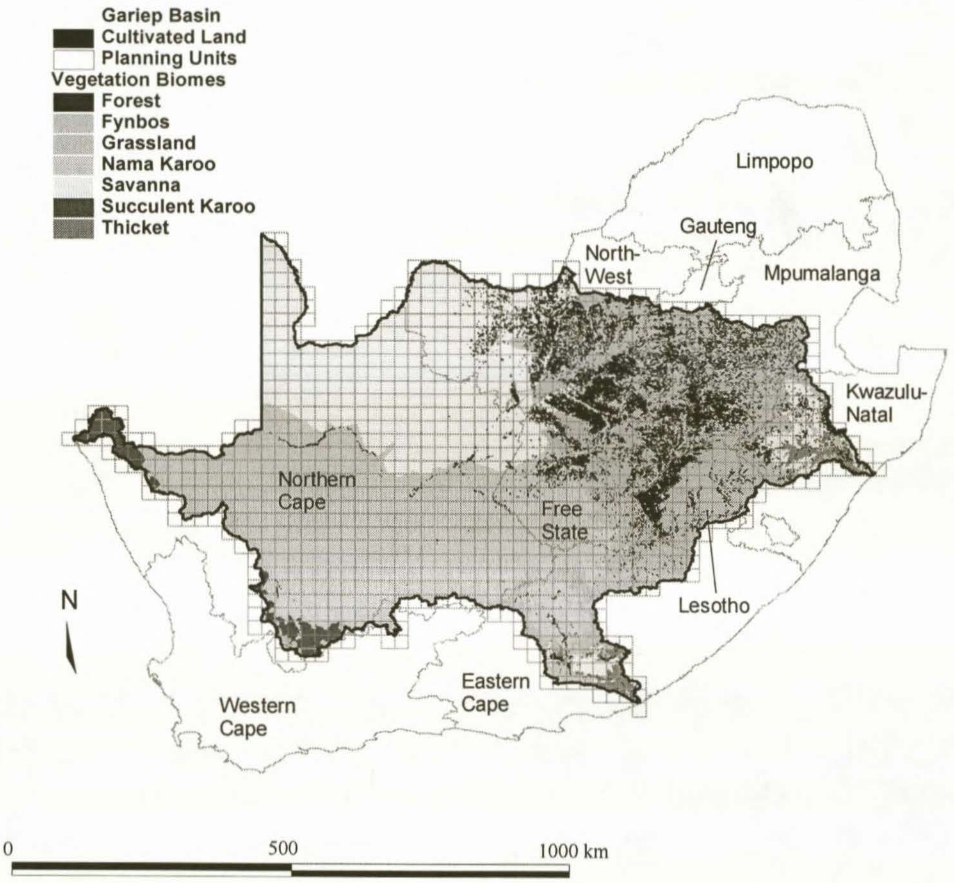

Figure 1. Gariep basin study area in South Africa showing each biome and the cultivated land as well as the division of the area into quarter degree grid squares.

Defining targets for biodiversity features is largely subjective. Target guidelines for areas are frequently set at a minimum of 10% of a region, be that a habitat type, vegetation type or biome (Pressey et al. 2003). In the absence of abundance and population data for species distributions, a single occurrence per species is commonly used as a representation target. Representation targets were increased to full representation of CR species in acknowledgement of their low numbers, their severe vulnerability and the urgent need for the conservation of these species. Other species of special concern (endemic, EN, VU and NT) remained at a single representation (see Rouget et al. 2004). Vegetation targets were adjusted by the natural rarity (NR) of each vegetation type and a measure of threat within the vegetation type (TH), determined by the formula described in Reyers (2003):

$$\text{TARGETVEG} = 10 \times (1 + \text{NR} + \text{TH}) \tag{Eq. 1}$$

where, TARGETVEG is the percentage of the original extent of each vegetation type; NR is measured as $(Am - Ai)/Am$ where Am is the area of the largest vegetation type in the region and Ai is the area of the vegetation type for which the target is being set (Reyers 2003). The South African national land cover database (Thompson 1996; Fairbanks et al. 2000) was overlaid with vegetation data to determine TH. This was calculated as the proportion of a vegetation type affected by transformation and degradation, and was determined by reclassifying the 31 land cover classes into 3 categories of natural, modified and transformed vegetation based on Fairbanks et al. (2000). NR and TH values range from 0 to 1 and final vegetation targets range from 10 to 30% of the original extent of each vegetation type.

Opportunity costs related to cereal production potential

Available data on agricultural arability or dryland suitability indicate little with regards to quantitative production values, which limits our ability to set quantitative production targets and determine the foregone opportunity cost to cereal production. Opportunity costs for cereal production potential were thus modeled using the only approach available developed for the Southern African Millennium Ecosystem Assessment (Scholes & Biggs 2004). This models total annual cereal production (in million tones - Mt) at a 5 x 5 km resolution. The model is based on simple crop growth models, adjusted to observed production in South Africa as given by the Food and Agriculture Organisation statistics (FAOSTAT) database, and restricted to cultivated areas based on the equation:

$$\text{Total CP (t)} = \sum_{\text{cereal}\,\alpha} \left[\left(\frac{\text{Observed total}\,\alpha\ \text{CP (t)}}{\text{Estimated total}\,\alpha\ \text{CP (t)}} \right) \times \text{Estimated}\ \alpha\ \text{CP (t) spatially distributed} \right] \tag{Eq. 4}$$

where CP is cereal production potential, t is the period of 1995-1999 over which all statistics were averaged and α is a specific cereal crop. The observed total CP as a proportion of the estimated total CP in South Africa is the adjustment factor that corrects the estimated cereal production per crop over the spatial extent of the basin, and fits the observed average total production for each cereal (obtained from the FAOSTAT database; FAO 2003). Estimated cereal production per crop over the spatial extent of the basin was calculated using the equation:

$$\text{Estimated } \alpha \text{ CP (t)} = \text{Cultivated area (ha)} \times \text{Fraction planted to cereal } \alpha \times \text{Maximum yield of cereal } \alpha \text{ (t/ha)} \times f(\text{growth days})_{\text{cereal } \alpha} \quad \text{(Eq. 5)}$$

where cultivated area was obtained from the sum of all cultivated land classes in the South African National land cover database (Thompson 1996). The assumption is made that agriculture has been practised in South Africa for some time, that commercial agriculture is well established and that therefore, agriculture is not going to experience considerable further extensification, but rather that intensification will be the trend (Biggs and Scholes 2002). A consequence of this however, is that cereal production potential may be slightly underestimated. The fraction of each cereal crop planted is the average area planted per cereal crop divided by the total area under cultivation for that cereal crop, based on data obtained from the FAOSTAT database (FAO 2003). Maximum yields per cereal are those under intermediate input levels given by the Global Agro-Ecological Zones study (FAO and IIASA 2000), where the maximum yields for maize, millet, sorghum and wheat are 5.3, 3.6, 4,6 and 3.4 t/ha respectively. Growth day functions were determined by relating the crop precipitation requirements given in FAO Ecocrop database (FAO 2003) to growth days. The relationship between annual precipitation and growth days was determined by linear regression (r^2=0.911, p<0.001, n=429444):

$$\text{Growth days} = 19.367 + 0.167 \times \text{Precipitation} \quad \text{(Eq. 6)}$$

Scaling the cereal productivity by the function of growth days, which is a factor of precipitation and varies spatially, generates the spatial distribution of cereal production potential across the Gariep basin.

In the Southern African Millennium Ecosystem Assessment, this model was used to generate cereal production potential surfaces for maize, sorghum and millet. We applied this model to maize, sorghum, millet and wheat. The inclusion of wheat is justified as this cereal makes the second largest contribution to meeting kilocalorie demands from cereal in South Africa (Nel and Steyn 2002). Although treating each cereal crop species separately and evaluating conflict with conservation per crop type would be preferable, this was not possible due to lack of data on the current spatial distribution of each crop species across the basin. The only spatial data available was for all cereal crop species combined, thus compelling the combination of all four crop species into one composite cereal production potential layer. Although the use of a single layer of production potential was necessary, maize, wheat, sorghum and millet differ in the fraction of land in the basin planted to each cereal, their maximum yields and crop precipitation requirements. Calculating each layer separately in the model improves accuracy. Thus cereal production potential for each cereal is determined separately for each 5km grid, and the 4 surfaces are summed to determine total cereal production potential for the basin. The cereal production potential at this $5km^2$ resolution was summed to an estimate of cereal production potential for each quarter degree grid square.

Cost thresholds

Demand for cereal can be established by determining the contribution of cereals to meeting the minimum daily kilocalorie requirements of the Gariep basin's human population. This is taken as the Recommended Daily Allowance (RDA), assumed to be 2100 kcal/person/day (Scholes and Biggs 2004). At least 54% (1134 kcal/person/day) of these daily requirements are provided by cereal (FAO and WHO 1998; Bohensky *et al.* 2004). The relative contribution of each cereal to this target is multiplied by the population and the number of days in a year to determine the total kilocalorie demand (see Eq. 5). This is divided by the kilocalorie content of each cereal α, taken from the Global Agro-Ecosystem Zones data (FAO and IIASA 2000), to determine the final cereal requirements in tons per year.

$$\text{Total cereal demand (t/yr)} = K\left[\frac{1134\ \text{kcal/person/day} \times \left(\dfrac{\alpha.\text{Cereal production}}{\text{Total cereal production}}\right) \times \text{Population} \times 365\ \text{days}}{\text{Kcal content } \alpha \text{ cereal (kcal/1000g)}}\right]$$

(Eq. 7)

where K is the conversion factor from kilograms to tons, the fraction of each cereal planted is based on data obtained from the FAOSTAT database (FAO 2003) averaged over the period 1995 to 1999 and population estimates for the Gariep basin and Lesotho were extracted from the South African population census data (StatsSA 2003) and the Lesotho Bureau of Statistics (2002) respectively.

Equation 7 provides a minimum production demand and the first cereal production target (target 1) (Table 2). Actual kilocalorie intake can be much higher than the recommended daily allowance and estimates of actual consumption rates of the different cereals types are included as a more accurate indication of human cereal demand (taken from

Nel and Steyn (2002)). Differences in consumption patterns between the different population groups in South Africa provide estimates of average adult consumption (adult defined as >10 years of age). These are calculated using two methods to determine combined estimates of food intake per province for different population groups. Method 1 did not take the ethnic group proportions in each province in South Africa into consideration. Method 2 did consider the proportion of ethnic groups per province. The two methods provide different estimates of average adult consumption. Method 2 differs from method 1 in that it estimates higher consumption of wheat and lower consumption of maize, estimating a lower overall target (target 2) from that calculated using method 1 (target 3). Nel and Steyn (2002) did not include millet in their models as it was not a commonly consumed cereal type. Millet contributes relatively little to target 1 (0.36%) justifying its exclusion from the calculation of targets 2 and 3. The overall targets are slightly overestimated by the assumption that, on average, every person consumes the equivalent of an adult. Cereals also contribute to protein intake but the total requirements to fulfil the protein needs of the population never exceeded those of kilocalorie demands and are thus already met by meeting kilocalorie demands.

The calculation of food demand in the southern African sub-region is not a simple, being influenced by complex factors such as politics, global trends and weather. There are numerous assumptions made in the calculation of these cereal targets, but it is proposed that the simple calculation of targets be used as a means of exploring the situation better. Assumptions include the suggestion that all people in the Gariep basin consume the same number of calories from cereal per day, which, due to issues of access and availability of resources, is inaccurate. The Gariep basin is treated as a closed system, an assumption that is flawed as it ignores cereal imports into and exports out of the basin. However, data on these imports and exports are currently lacking, as are data for cereal demands for non-consumptive cereal use (such as livestock feed and seed), and are excluded from the calculation of cereal targets. While these factors are an important part of the economy, providing towards human well-being in the basin in numerous ways, they are more difficult to estimate reliably. As further data become available they can be included into the model to more realistic cereal demand estimates.

Table 2. Calculation of food demand targets given in million of tones (Mt) for four cereal types in the Gariep Basin. These are based on minimum daily nutritional requirements (Target 1) and two methods for estimating the actual consumption rates in South Africa (Target 2 and 3).

	Maize	*Millet*	*Sorghum*	*Wheat*	*Total*
Production in SA & Lesotho (Mt/yr)	8.290	0.038	0.368	2.172	10.868
Production in SA & Lesotho (g/yr)	7.875E+11	3.690E+09	3.720E+10	2.650E+11	1.093E+12
% of total	72.02	0.34	3.40	24.24	100.00
Contribution to daily protein requirements [a]	21.35	0.10	1.01	7.18	29.64
Cereal protein content (g/1000g)	95	97	101	122	
Total protein requirements (Mt/yr) [b]	1.932	0.009	0.086	0.506	2.533
Production in SA & Lesotho (kcal/yr)	2.951E+13	1.293E+11	1.263E+12	7.255E+12	3.816E+13
% of total	77.34	0.34	3.31	19.01	100.00
Contribution to daily calorie requirements [c]	877.00	3.84	37.55	215.61	1,134.00
Cereal calorie content (kcal/1000g)	3560	3400	3430	3340	
Total calorific requirements (Mt/yr) [b]	2.118	0.010	0.094	0.555	2.777 (Target 1)
Method 1 [d]: Average per capita (g/capita/day)	690.06		1.67	152.8	
Average demand (Mt/yr)	5.933		0.014	1.314	7.261 (Target 3)
Method 2[d]: Average per capita (g/capita/day)	475.57		1.42	160.63	
Average demand (Mt/yr)	4.089		0.012	1.381	5.482 (Target 2)

[a] *Minimum daily protein requirements from cereal types is 29.64g*

[b] *For the Gariep population of 20.97 million*

[c] *Minimum daily kilocalorie requirements from cereal types is 1134 kcal*

[d] *Extracted from Nel and Steyn (2002)*

Using the total cereal production potential of the Gariep basin and the three cereal production targets described above, four cost threshold values are defined. A cost threshold is defined as the amount of cereal production that can be lost before we are unable to achieve the set cereal target. It is calculated here as:

$$\text{Cost threshold} = \text{Total cereal production} - \text{Cereal production target} \tag{Eq. 8}$$

where a low target gives a high cost threshold. Once the threshold is exceeded the reserve solution is penalised. So with a higher threshold a lot of cereal could be lost (land is used for conservation) without affecting the ability of the region to achieve its cereal target, and without the reserve solution incurring a penalty. The first cost threshold (full threshold) has a cereal production target of 0 and sets the cereal production threshold at the net cereal production potential of the Gariep basin (5.620 Mt/yr). This allows the full cereal production value to be utilised before the objective function is penalised. The second and third cost thresholds are calculated from the subtraction of target 1 (high threshold = 2.741 Mt/yr) and target 2 (medium threshold = 0.138 Mt/yr) from the net cereal production potential of the basin. As target 3 is greater than the total cereal production potential available, the fourth cost threshold (low threshold) is set close to zero, at 0.1 t/yr (a cost threshold of zero deactivates the cost threshold function).

MARXAN parameters

The cost of sites is taken as the potential cereal production value. Three conservation feature penalty factors were used. The first two assigned the same penalty factor to all conservation features, namely a penalty factor of 1,000 (low conservation feature penalty factor) and 100,000 (high conservation feature penalty factor). The third conservation feature penalty factor (combination conservation feature penalty factor) uses a combination of penalty factors, assigning a high penalty factor (100,000) to critically endangered species and a low penalty factor (1,000) to all other conservation features.

For each of these three conservation feature penalty factors, reserve solutions are generated with and without the cost threshold penalty activated. Solutions with the cost threshold penalty activated use the four cost threshold values (Eq. 8) with two different combinations of two control parameters (see table 1). The first combination uses parameters that allow the threshold to be exceeded only marginally, penalizing any excess of the threshold. This allows a solution that places more importance on the achievement of biodiversity targets and is referred to as the *lenient planning scenario*. The second combination of parameters greatly penalizes reserve solutions that exceed the cost threshold and is referred to as the *strict planning scenario*.

Using all combinations of the three conservation feature penalty factors, the four cost threshold values, no cost threshold, and the two planning scenarios under each threshold, 27 different reserve problems are posed (Table 3). Using simulated annealing as the primary area selection algorithm, a fixed annealing schedule, determined through careful evaluation of many runs, was used. All solutions were generated over 100 runs, with 1,000,000 iterations and 10,000 decreases (Andelman et al. 1999; Ball and Possingham 2000; Ardron et al. 2002). The summed irreplaceability heuristic and normal iterative improvement algorithms were used in combination with simulated annealing (Ardron et al. 2002). With 100 runs per reserve problem, 2,700 reserve solutions were generated and the best solution for each of the 27 reserve problems identified.

Performance evaluation of potential reserve solutions

Comparison of results under different planning scenarios is achieved using a number of performance measures. Three primary outputs of MARXAN were assessed:

(i) the best reserve solution for each reserve problem is identified as the one with the lowest objective function score, and is mapped in a geographical information system (ArcView 3.2 - ESRI 1999) with the help of an interface software between ArcView and MARXAN (CLUZ – Smith 2003);

(ii) proportional overlap was also used to test the spatial overlap between reserve solutions. Proportional overlap measures the spatial overlap as a proportion of the maximum overlap possible using the equation:

$$\text{Proportional overlap} = N_c/N_s \tag{Eq. 9}$$

where N_c is the number of common grid cells in a pair of priority surfaces and N_s is the number of grid cells in the smallest priority surface containing data for both groups, or in other words the max number of overlapping grid cells possible (Prendergast et al. 1993; Reyers et al. 2000);

(iii) the frequency with which a site was selected, (selection frequency) over a series of runs gives a measure of how important that site is to the final reserve solution (Ball & Possingham 2000). Spearman rank correlation was used to test the degree of correlation between the frequency of selection under different planning scenarios.

The performance of potential reserve solutions were also evaluated using some of the additional summary data generated in MARXAN. Summary data included measures of the objective function score, the number of sites in the reserve solution, the overall opportunity cost, and the number of biodiversity features whose targets are not met in the reserve solution. Other measures evaluated included the number of sites selected in a reserve solution that coincide with the 10% highest cereal producing sites.

Table 3. The 27 reserve solutions analysed are generated with three conservation feature penalty factors (CFPF – low, combination and high) for objective functions with no cost threshold (CT) applied (none – 1, 10 and 19) and for objective functions with four different cost thresholds (full, high, medium and low cost threshold values) applied under two planning scenarios (lenient and strict).

CFPF	*Low*		*Combination*		*High*	
CT	*Lenient*	*Strict*	*Lenient*	*Strict*	*Lenient*	*Strict*
None	1		10		19	
Full	2	6	11	15	20	24
High	3	7	12	16	21	25
Medium	4	8	13	17	22	26
Low	5	9	14	18	23	27

RESULTS

The total cereal production potential of the Gariep basin is estimated at just over 5.620 Mt/yr. The distribution of this cereal production potential is spread unevenly across the basin (Figure 2a). The variation in cereal production potential, with higher cereal production potential in the eastern regions of the basin, is influenced by South Africa's precipitation pattern, which has a strong east to west gradient with much of the dry western half of the basin receiving less than 400mm precipitation per annum (Figure 2b) and with a poor potential to produce cereal.

Best solutions

A primary output of MARXAN is the selection of a set of sites that have the best objective function score in comparison to all other solutions generated at each run. These solutions are illustrated in Figure 3, which highlights the overlap between lenient and strict planning scenario solutions. As illustrated in Table 3, the lenient and strict planning scenarios are only applied where a cost threshold is set (i.e. excluding those that have no cost threshold set).

When cost thresholds are high, reserve solutions that do not exceed the cost thresholds are easily found. At high thresholds, there is also little dissimilarity between reserve solutions under the lenient and strict planning scenarios (Figure 3a – f). The proportional overlap at full cost threshold is between 93.8% and 94.7%, and at high cost threshold it is between 92.6% and 93.9%. Here a penalty for exceeding the cost threshold is never incurred and can therefore not outweigh the penalty for not achieving biodiversity targets. In these instances the conservation feature penalty factor does not visibly influence the solutions generated.

At lower cost thresholds, representing all biodiversity without exceeding cost thresholds becomes difficult and penalties for exceeding the thresholds are incurred. At these lower thresholds the planning scenario used does influence the penalty incurred. The proportional overlap between sites selected under the strict and lenient planning scenarios decreases (Figure 3g – l). Penalties for exceeding the threshold are inflicted very quickly under the strict planning scenario, training the selection away from sites with high cereal production potentials. Thus sites selected under the strict planning scenario lie more in the western half of the basin where cereal production potential is low or zero. Under the lenient planning scenario, penalties are not inflicted as rapidly and the selection of sites is allowed to exceed the cost threshold more frequently, hence the larger number of sites in the high cereal production potential areas.

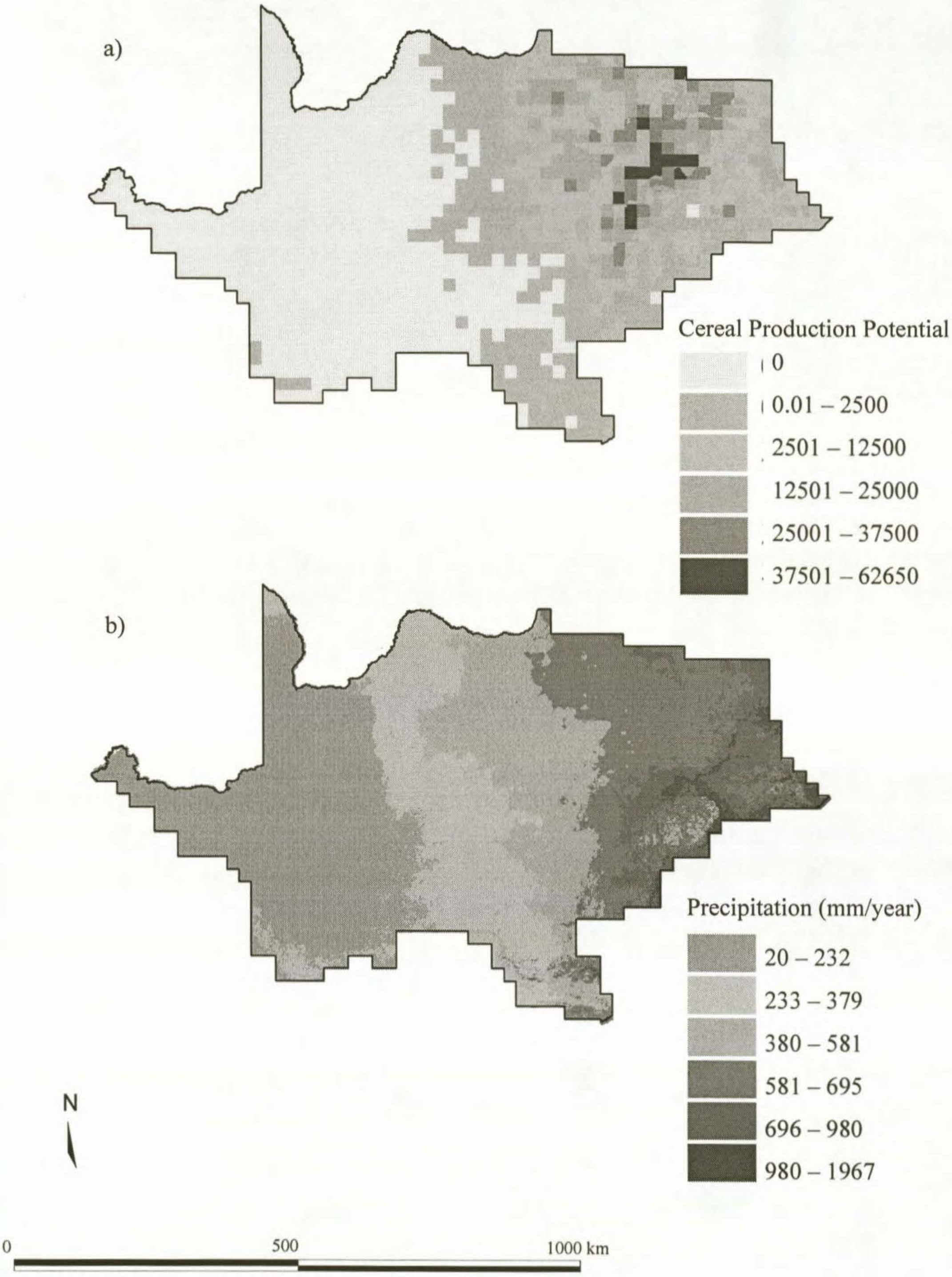

Figure 2. The Gariep basin of South Africa with (a) cereal production potential higher in the eastern half of the basin where (b) annual precipitation is also higher.

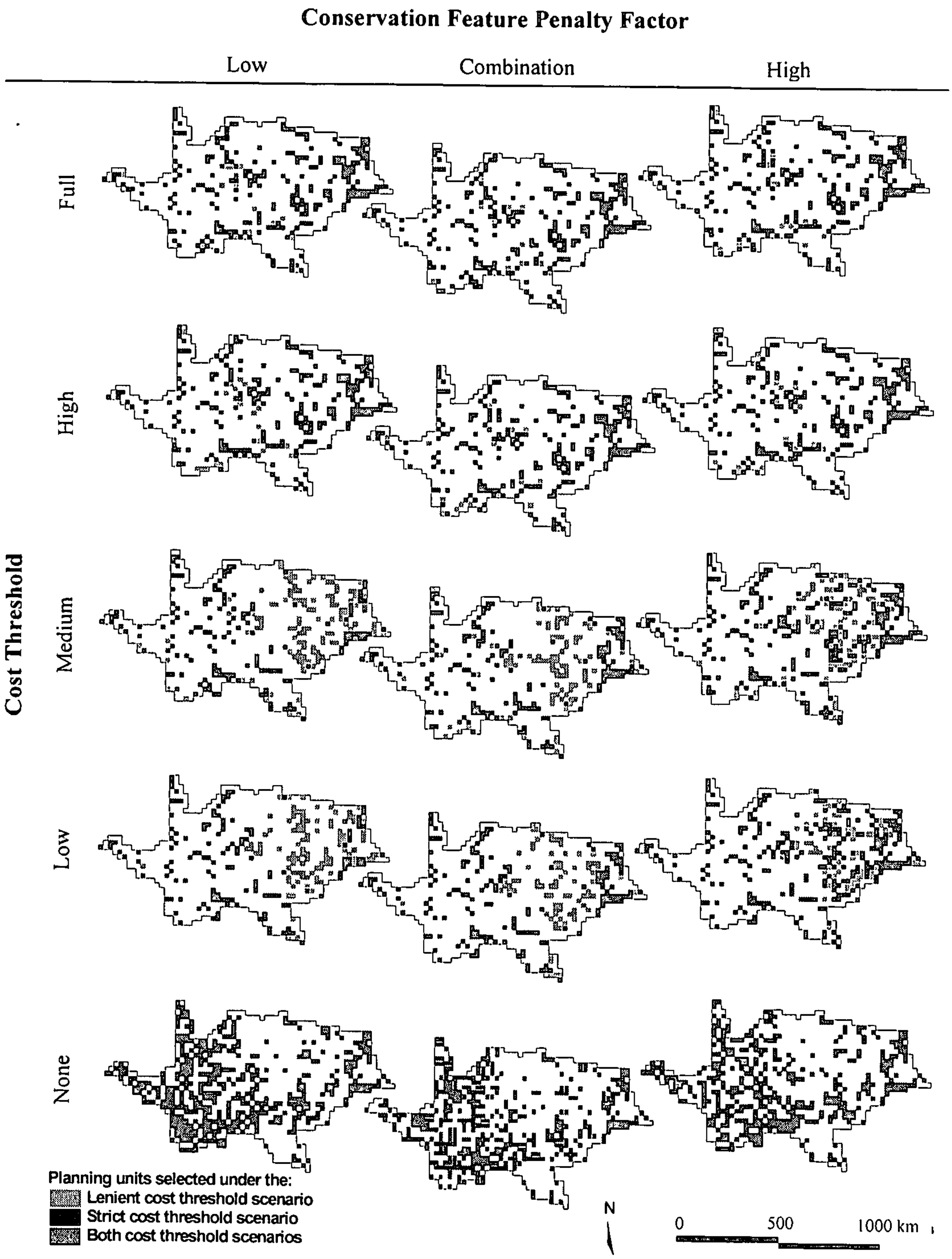

Figure 3. The best reserve solution generated for 27 reserve problems using three conservation feature penalty factors (low, combination and high thereof, where critically endangered species are given high conservation feature penalty factors and the rest are given low), five cost thresholds for cereal production potential and two planning scenarios (lenient and strict). Planning scenarios are not applicable to the problems with no cost threshold set. The overlap between the lenient and strict scenarios at the other four cost threshold under each conservation feature penalty factor are illustrated.

The penalties incurred for exceeding the cost threshold are weighed against those incurred for not meeting biodiversity targets. This means that at high conservation feature penalty factors, the difference between the reserve selections under the strict and lenient planning scenarios is not as evident, as high penalties for conservation force the algorithm to select sites with high cereal production potential to represent all conservation features. Thus, the proportional overlap between lenient and strict solutions is 73.9% at the medium cost threshold and 78.3% at the low cost threshold, while much of the overlap occurs in the poorer cereal production areas of the western Gariep basin. There is also a much higher variation in sites selected in the more productive eastern areas. Although there appears to be less overlap under the low and combination conservation feature penalty factors, the overlap between strict and lenient planning scenarios is >89%. This higher percentage is due to the smaller number of total sites selected under the strict planning scenarios in these solutions.

The proportional overlap between the no cost threshold solutions is >65% (Figure 3m-o). The selected sites in these solutions are largely concentrated in the western region of poor cereal production potential. Sites selected in the eastern half of the basin are those contributing greatly towards achieving conservation feature targets.

Selection frequency

The selection frequency of sites over 100 runs for each reserve problem is illustrated in Figures 4. The number of sites not selected, selected in at least one run, and the number selected in all runs illustrates a degree of similarity between the reserve solutions. General groupings of solutions, based on their similarity to each other, can be identified from this graph. The percentage of sites selected 100 times, and those selected at least once are very similar in reserve problems with full and high cost thresholds (Spearman $R > 0.999$, $df = 1109$, $P < 0.05$). These reserve solutions have the highest percentage of sites selected 100 times in comparison to all other reserve solutions. Regardless of the conservation feature penalty factor imposed, reserve solutions at the medium cost threshold under the lenient planning scenario are all very similar (Spearman $R > 0.999$, $df = 1109$, $P < 0.05$), as are those at the low cost threshold under the lenient planning scenario (Spearman $R > 0.999$, $df = 1109$, $P < 0.05$). Reserve solutions with no cost threshold applied can also be grouped as being very similar. These reserve solutions have the smallest percentage of sites selected 100 times and the highest percentage selected between 1 and 99 times. It is only at the medium and low cost thresholds under the strict planning scenario that the frequency of selection within a scenario differs between reserve solutions with different conservation feature penalty factors.

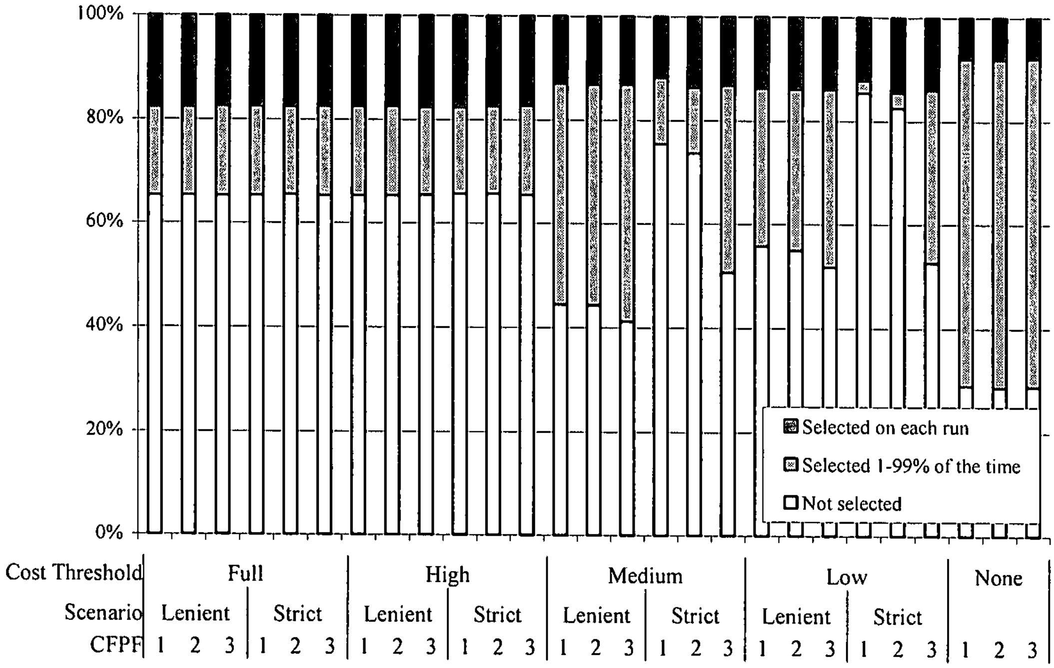

Figure 4. Percentage of sites selected in 100 percent, less than 100 percent but more than 0 percent, and not selected in any of the runs in each planning problem. Solutions are listed by their cost threshold, the planning scenario and the conservation feature penalty factor (CFPF) used.

Under the strict planning scenario at both medium and low cost thresholds, the reserve solutions for low and combination conservation feature penalty factors are different from those with a high conservation feature penalty factor. The percentage of sites selected more between 1 and 99 times is considerably smaller under the strict planning scenario with low and combination conservation feature penalty factors. The frequency of selection of sites with a high conservation feature penalty factor is more similar to the solutions under the same cost threshold but with a lenient planning scenario. A high conservation feature penalty factor forces the algorithm to achieve biodiversity targets even though the cost thresholds are exceeded. Similar answers were grouped and the different spatial distributions of these groups are compared in Figure 5. These surfaces provide an indication of the utility of the respective sites to achieve these solutions.

Figure 5a shows the frequency of selection of sites for reserve solutions with full and high cost thresholds. These cost thresholds are easy to achieve and there is little difference between solutions under different planning scenarios or with different conservation feature penalty factors. Most sites selected between 1 and 99 times in these solutions have very low cereal production potential, indicating that the algorithm tries to avoid sites with high cereal production potential. However as the cost thresholds are high, this is not a very strong driving force indicated by the sites that are selected 100 times being scattered over the basin and not restricted to those crucial for achieving the biodiversity targets set. This is different to the reserve solutions for which no cost threshold was imposed (Figure 5b) where it is only sites that are essential to achieving conservation targets that are selected 100 times. Isolating sites crucial for achieving conservation targets is important for evaluating trade-offs later on. In figure 5b, sites with no cereal production potential are all selected at least once. The variation in the frequency of selection of sites with cereal production potential in the central eastern regions is greater in figure 5b than it is in figure 5a.

Reserve solutions for low and medium cost thresholds under lenient planning scenarios are very similar to each other (Figure 5c and d). There is considerable variation in the selection frequency of sites with cereal production potential in the central eastern regions of the basin. In contrast, reserve solutions exhibited in figure 5e and f (low and medium cost thresholds under the strict planning scenario with low and combination conservation feature penalty factors) display remarkably little variation in the selection frequency of the central eastern areas with cereal production potential. This indicates that at under the lenient planning scenario at these low and medium cost thresholds the algorithm still searches for solutions that may include sites with high cereal production potential costs. However under the strict planning scenario with low and combination conservation feature penalty factors, the algorithm largely ignores sites with cereal production potential as the conservation feature penalty factors are low.

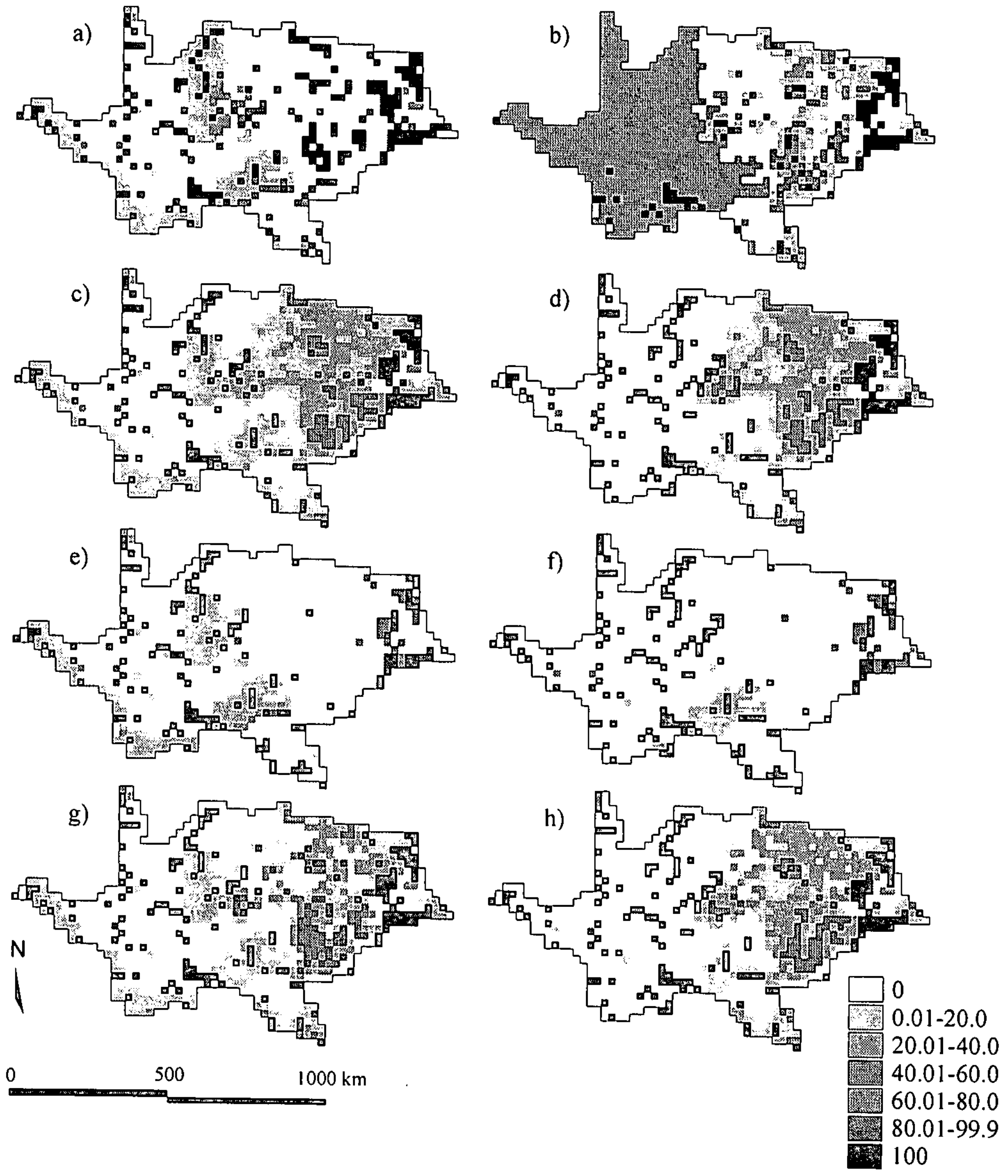

Figure 5. Frequency of selection of sites in 27 reserve planning problems selected using simulated annealing. The frequency of selection for reserve solutions with full and high cost thresholds (a), with no cost threshold (b), and with medium (c, e and g) and low cost thresholds (d, f and h), where (c) and (d) is under the lenient planning scenario with all conservation feature penalty factors, (e) and (f) are under the strict planning scenario for the low and combination conservation feature penalty factors, and (g) and (h) are under the strict planning scenario with the high conservation feature penalty factor.

The penalty incurred for selecting sites with cereal production potential under strict planning scenario is greater than the penalty incurred if conservation targets are not achieved. Figure 5c and d are most similar to figure 5g and h, which have low and medium cost thresholds under the strict planning scenario but with high conservation feature penalty factors. The combination of the strict planning scenario with the high conservation feature penalty factor forces the algorithm to consider sites with higher cereal production potential, as the penalty for not achieving conservation targets is high.

Overall, variations in the selection frequencies are evident at lower cost thresholds where the combination of the planning scenario used (strict or lenient) with the conservation feature penalty factor applied influence the selection of sites. It is the number of sites not selected at all and those selected between 1 and 99 times that varies most across different reserve problems. In total, 43 sites are selected 100 times in all reserve solutions. These are thus crucial to all reserve solutions. However it is only in the solutions for which no cost threshold is set that sites selected 100 times are representative of those that are crucial to achieving conservation targets. In all solutions where a cost threshold was applied, not all sites selected 100 times are crucial to achieving conservation targets although they are crucial to achieving a particular range of solutions.

Cost, targets and area

The differences already highlighted between reserve solutions can be further examined with the aid of the summary results of best solutions (Table 4). For the full and high cost thresholds, regardless of the penalty factor or the planning scenarios adopted, the foregone cereal production potential is 18.5% and the area required is consistent at just under 21% of the Gariep basin. The cost thresholds are not exceeded in these reserve solutions and all conservation feature targets are met. There are always 18 sites with the 10% highest cereal production potential in the reserve solutions and the objective function scores are identical.

The influence of the planning scenarios and the conservation feature penalty factors used is most evident at the medium and low cost threshold solutions. For these solutions, and under the strict planning scenario with low and combination conservation feature penalty factors imposed, sites in the eastern regions of the basin were not selected (illustrated in Figure 5e and f above). A consequence of this is the failure to achieve biodiversity targets, although with some substantial benefit to cereal production. Imposing a low conservation feature penalty factor for this problem reduces the number of sites selected which have high cereal production potential to one or zero, incurring a cost of less than 3% to cereal production but also failing to achieve 25 or more biodiversity features. Some of these features include critically endangered species (percentage of target achieved given in parenthesis): Chrysospalax villosus (60%), Botaurus (50%), Bugeranus (54%), Mirafra ruddi (57%) and Hirundo (66.7%). Seven vegetation types have less than 10% of their target represented. Two are in the Savanna biome, four in the Grassland biome and one in the Forest biome. Using a combination conservation feature penalty factor, which applies a higher penalty factor for some conservation features, more conservation features achieve their targets, but at a greater cost to cereal production (8.85% of total cereal production potential). All conservation features that are critically endangered are included in these solutions. All species achieve their targets except for three frog species. Six vegetation types have less than 10% of their target represented: two are in the Savanna biome, three in the Grassland biome and one in the Forest biome.

Still at low and medium cost thresholds, reserve solutions under the lenient planning scenario achieve all conservation targets but at a higher cost to cereal production. Additionally, a greater number of high cereal production areas are selected and the area required is larger. A similar result, but under the strict planning scenario is only achieved at the low cost threshold with a high conservation feature penalty factor imposed. The only reserve solution that comes close to those achieved with full and high cost thresholds is achieved under the strict planning scenario with a high conservation feature penalty factor, but at a medium cost threshold. This particular reserve solution in fact improves upon those at full and high cost thresholds by reducing the number of selected sites with high cereal production potential.

Such subtle differences suggest high sensitivity to the balance between penalty factors for cost thresholds and the representation of conservation feature targets. For low and combination conservation feature penalty factors, the objective function is penalised more severely for exceeding the cost threshold than it is for not achieving all conservation feature targets. But in terms of minimising cost to cereal production and representing all biodiversity feature targets, the best overall solutions are generated by the reserve solutions for which no cost threshold is set. In this instance, the cost to cereal production drops to approximately 16% of the total cereal production potential, 2.5% lower than any reserve solution with a cost threshold set. The number of high cereal production sites selected is also lower, but the number of sites selected overall is almost double the number selected in other solutions. The reduction in cereal production potential lost, comes at a cost to area. But there is no obvious reason as to why the other reserve solutions did not take advantage of this, when many sites have very low and even no cereal production potential. The sites with high cereal production potential that could not be avoided in reserve solutions are indicative of areas that will be hard to avoid as long as the representation of all biodiversity feature targets is a priority. These sites lie largely in the central and eastern cereal production areas and are only avoided by solutions that fail to represent all conservation features. Most of these sites contain critically endangered species, which accounts for the fact that they cannot be avoided unless the representation of these species is sacrificed.

Table 4. Summary data for the best reserve systems generated using a simulated annealing algorithm for 2 planning scenarios with 3 combinations of conservation feature penalty factors at 4 different cost thresholds (solutions numbered 1-24). Cost is given as the percentage of the total annual cereal production potential of the Gariep basin (5620570 tonnes).

Scenario	*Cost Threshold*	*Soln No.*	*Score (millions)*	*Cost %*	*No. missing features*	*No. sites*	*No. PU's in top 10% cereal production*
		Low Conservation Feature Penalty Factor					
	None	1	0.895	15.93	0	440	12
Lenient	Full	2	1.040	18.50	0	230	18
	High	3	1.040	18.50	0	232	18
	Medium	4	1.289	22.94	0	245	23
	Low	5	1.234	21.95	0	239	20
Strict	Full	6	1.040	18.50	0	232	18
	High	7	1.040	18.50	0	229	18
	Medium	8	1556.192	2.51	25	146	1
	Low	9	1904.074	1.48	28	138	0
		Combination Conservation Feature Penalty Factor					
	None	10	0.901	16.02	0	423	13
Lenient	Full	11	1.040	18.50	0	226	18
	High	12	1.040	18.50	0	230	18
	Medium	13	1.346	23.94	0	241	25
	Low	14	1.238	22.02	0	238	23
Strict	Full	15	1.040	18.50	0	234	18
	High	16	1.040	18.50	0	228	18
	Medium	17	445.822	8.85	17	167	9
	Low	18	445.822	8.85	17	164	9
		High Conservation Feature Penalty Factor					
	None	19	0.905	16.11	0	404	14
Lenient	Full	20	1.040	18.50	0	225	18
	High	21	1.040	18.50	0	230	18
	Medium	22	1.421	25.28	0	245	24
	Low	23	1.422	25.30	0	247	26
Strict	Full	24	1.040	18.50	0	232	18
	High	25	1.040	18.50	0	232	18
	Medium	26	1.043	18.55	0	234	16
	Low	27	1.376	24.49	0	245	26

DISCUSSION

Reserve solutions are a direct function of the constraints imposed by the reserve design problem (Stewart et al. 2003). The effect of setting spatial constraints and targets in the reserve selection approach have been investigated in a number of studies, but the effect of the cost threshold parameters and conservation feature penalty factors have not been explored. This study utilises the cost threshold option and the setting of different conservation feature penalty factors to investigate the disparate outputs they generate. Although not a comprehensive sensitivity analysis, this study attempts to investigate the effects of these parameters on potential reserve solutions.

The trade-off between penalties: cost threshold penalties and conservation feature penalty factors

The setting of a cost threshold inflicts a penalty on the objective function of the reserve solution when site costs exceed the threshold. Simply activating the cost threshold function impacts the reserve solutions acquired. This is the case, even when the threshold is so high that it will not be exceeded and therefore should not constrain the algorithm solution. When the cost threshold function is activated, the most evident impacts on the resulting reserve solutions are at thresholds that are exceeded during the reserve selection and thus incur a penalty. This is fairly intuitive as penalties are designed to alter the reserve selection, but the impact that the activation of the cost threshold has on reserve solutions is less intuitive and the available literature provides no explanation for this.

An interesting side effect of reserve solutions for objective functions in which the cost threshold function is activated is that they are less area intensive. When the cost threshold function is not activated, there is an apparent inability to place constraints on the area selected in MARXAN when a cost other than area, such as cereal production potential, is being minimised. This is a drawback as it limits the usability of the cost field if such costs have many zero values, such as with the cereal production potential data used here, and encourages the selection of large areas of land with no added cost to the objective function. The large areas selected likely inflict higher opportunity costs on alternative land uses. A site's cost could be altered to include its area, which would ensure no zero values, but this would make the application of a sensible cost threshold impractical. It is unclear as to why the cost threshold function appears to minimise the area selected although the addition of sites with zero cereal production potential would be at no extra cost to the objective function.

A third aspect of the cost threshold that requires clarification is the manner in which the algorithm is constrained by low cost thresholds. It seems that more efficient solutions are found when the cost threshold is greater than the lowest value it can be to meet all conservation targets without exceeding the cost threshold, in other words greater than the cost to cereal production potential in an optimal solution. If cost thresholds are lower than this optimal value, then the cost to cereal production potential becomes lower than that incurred by solutions at higher cost thresholds, but only when some conservation features are underrepresented. Thus, in practice, the optimal cost threshold value will have to be found first to determine the lowest possible cost threshold, below which cost thresholds should not be set. The value of this function to explore real targets and thresholds then possibly becomes reduced. Obviously spatial solutions that meet all objectives as thresholds get lower are going to be more difficult to find, but these solutions should surely not be worse than the solutions achieved under higher thresholds. This said, there seems to be a close relationship between the cost thresholds set and the conservation feature penalty factor used. Solutions similar to those achieved at higher cost thresholds were found for the medium cost thresholds when a higher conservation feature penalty factor was introduced. If the conservation feature penalty factor is not high enough, other penalties outweigh the penalty associated with the under-representation of conservation features, and these features will not be fully represented. It may be that reserve solutions to difficult problems can be improved by stricter constraints on the algorithm. It is also probable that solutions would benefit from a longer running time (more iterations and repetitions).

Moreover, it is also possible that the less efficient solutions at lower cost thresholds are related to the combined use of additional area selection algorithms that run after the simulated annealing algorithm. Exploratory reserve solutions run on the same reserve problems and parameters without the summed irreplaceability approach activated in MARXAN, resulted in reserve solutions that do display a decreasing cost to cereal production with lower cost thresholds. This is what is expected. However, these solutions required much larger areas and the foregone cereal production potential was still higher than that incurred in the solutions presented where the summed irreplaceability heuristic was applied. The subsequent application of the additional summed irreplaceability heuristic therefore improves upon the reserve network selected by the simulated annealing algorithm and by normal iterative selection alone. This could indicate that other selection approaches may provide slightly different and perhaps even better solutions to the reserve problems presented here. It also points to the value of further investigations into the combined usage of these area selection procedures.

With regards to the under-representation of some conservation feature targets, this variable is related to the conservation feature penalty factor and the cost threshold control parameters. The cost threshold control parameters control how quickly the objective function is penalised when the cost threshold is exceeded. Using two sets of cost threshold control parameters provides a means of exploring trade-offs. This is achieved by allowing a controlled degree of leniency around the defined cost thresholds. Strict planning scenarios encourage the algorithm to find reserve solutions that stick more rigidly to the cereal production thresholds. At low cost thresholds with strict cost threshold control parameters, conservation features with low conservation feature penalty factors are not fully represented in reserve solutions - the penalty associated with their loss did not outweigh the penalty associated with exceeding the cost threshold. However with lenient cost threshold control parameters, conservation feature targets were always achieved and the penalty of exceeding the cost threshold never outweighed the penalty of under-represented conservation features. This is useful when investigating rough cost threshold estimates, which do not have to be strictly adhered to. Applying different conservation feature penalty factors to different conservation features provides further control over which conservation features are heavily penalized. It may be that conservation features that can be afforded partial protection outside of protected areas, or those that are likely to persist in cultivated lands could be assigned lower conservation feature penalty factors. This could help investigate other potential reserve solutions and provide additional points for negotiation, although the under-representation of conservation features is not usually an option. In most cases, the achievement of conservation targets is not up for negotiation. Conservation targets are frequently based on minimum thresholds (vegetation) and minimum representation (species), below which severe decreases in the species richness would occur (Lindenmayer & Luck 2005). It is rather the spatial distribution of reserve solutions that can be most easily negotiated.

The sensitivity of reserve solutions to planning parameters and the use of the cost threshold penalty and conservation feature penalty factor in MARXAN still require some explicit research into how robust simulated annealing is to variation in data types and uncertainty, and their exact function (Possingham et al. 2000). In the meantime, caution must be taken in setting planning parameters and interpreting results. Ardron et al. (2002) for instance, expressed caution in using the cost threshold function. As the site costs are meant to balance the conservation feature values gained they warn, "unless all scores are normalised across the board, unsatisfactory results can occur". Instead, Ardron et al. (2002) consider alternative approaches to including site cost information into their conservation assessment. Users of the conservation planning software platform and users of the final outputs must both be aware of the sensitivity of the reserve solutions to the numerous planning parameters defined by the software user.

Exploring solutions (selection frequency) and trade-offs

One of the important benefits of the simulated annealing approach is the generation of a number of different reserve solutions. This is due to the random element in selecting sets of areas which ensures that, with a sufficiently diverse set of features, no two runs are likely to produce exactly the same results (Ball and Possingham 2000; Ardron et al. 2002). The number of times a site is selected in a reserve solution provides a measure of the relative importance of a site for achieving a solution to a particular reserve problem (Ball & Possingham 2000; Day et al. 2002). This measure is sometimes referred to as the 'irreplaceability' of sites (Ball & Possingham 2000; Day et al. 2002). However, not all sites that are selected in every reserve solution generated over a number of runs are irreplaceable, and the term 'irreplaceability' may cause unnecessary confusion. The measure is not a real measure of site 'irreplaceability' as defined by Ferrier et al. (2000), which is based on a very different set of assumptions (Ferrier et al. 2000; Ardron et al. 2002). It is unlike irreplaceability in that, although it does indicate the importance of sites for achieving a reserve solution, it is dependent not only on the conservation features present in the sites, but on other criteria, such as spatial and cost constraints. Other studies have used different terms to describe this measure. Ardron et al. (2002) refer to sites with high frequencies of selection as having high *utility*, in that they "represent places that appear to be the most useful in the development of optimal reserve network solutions", while Day et al. (2002) refer to the "*flexibility* of a site to be replaced by another in achieving the required target for the conservation feature". Stewart et al. (2003) provide a method of calculating a meaningful measure of whether a site is selected more often than random in calculating the "frequency of all the reserve systems to which a site belongs out of the total number of systems generated" and refer to this measure as "summed irreplaceability". To ensure clarity, this study refers to this measure simply as the *selection frequency* of sites in the achievement of reserve solutions to a particular reserve problem.

The degree to which the selection frequency is influenced by different reserve problems and planning parameters is useful for investigating the impact of the parameters used. The frequency with which sites are selected helps to discern general trends in the selection process. It illustrates the degree of flexibility available for solving a particular reserve-planning problem. Such flexibility is useful for negotiating reserve solutions and spatial boundaries. Areas with high selection frequency are important for achieving a reserve solution. Those areas of high selection frequency that still overlap with areas of high cereal production potential, are unlikely to be avoided if all conservation features are to be represented. These would represent areas where trade-offs are likely to be unavoidable or have to be achieved at finer scales of planning. But depending on the parameters used, the number and spatial distribution of some of these vary. A small subset does remain the same and an idea of the truly irreplaceable sites might be a useful addition when considering planning options.

Overall, the use of an objective function with penalties instead of constraints in simulated annealing is useful in that it offers both flexibility (leniency, number of solutions) and efficiency (still tries to minimize cost) (Possingham et al. 2000). Consideration of cost (and other social, ethnic and economic factors) has its place in traditional conservation planning at the final stages of reserve selection. But consideration earlier on in the process could facilitate better understanding and better solutions, and possibly even alleviate inevitable problems and concerns at the end. The ability to include opportunity costs of other land uses simultaneously, which does not require the prioritisation of any one objective above another (such as in iterative approaches) and seeks to find a solution that best achieves all objectives, is appealing. MARXAN succeeds in finding good solutions. The cost to cereal production potential is decreased with an inevitable increase in the area required. Alternatively, with a slightly higher cost to cereal production potential a much smaller area is required and areas of high cereal production potential are avoided as much as possible. The very fact that numerous solutions can be generated for the same problem and that their relative merits can be evaluated in detail is an important characteristic of MARXAN that can aid in making trade-off decisions. MARXAN provides a true trade-offs approach where the minimisation of cost and maximisation of conservation feature targets can be considered simultaneously.

A number of reserve solution options that maximises conservation of biodiversity features and minimises cost to cereal production potential exist for regional planning in the Gariep basin. Solutions that truly minimise the cost to cereal production are area intensive, particularly in the dry western half of the basin. However, the achievement of conservation feature targets necessitates the conservation of a number of sites in the higher cereal production areas of the eastern half of the basin. Trade-offs in this region are unavoidable, although the number of areas that require trade-offs can be minimised in some simulated annealing solutions. Sites that have high potential for conflict under all options indicate areas that need to be prioritised for more detailed planning. Naturally, outputs are highly dependent on the data used and targets set (Csuti et al. 1997; Margules et al. 2002; Sarker & Margules 2002; Williams et al. 2002; Lombard et al. 2003). Finer scale planning could improve the efficiency of plans and their long-term conservation success would be improved with the use of more representative biodiversity surrogates and the inclusion of ecological processes.

As conservation programs and planners become more sophisticated in their inclusion of socio-economic and political factors in addition to the biological ones already used, conservation plans themselves require more and more insight into their meaning and implications. Explicit, specific goals are required for area selection algorithms, and as inputs get more complex and we start to come to grips with key uncertainties (e.g. climate change), sufficient technical expertise is required. As many have identified, the challenge will be to explore scenarios that anticipate the implications of future demands on land use and climate change and what the implications are for biodiversity conservation (Faith 2001a; Mier et al. 2004; Pressey et al. 2004). With comprehensive sensitivity analyses, which makes explicit the assumptions and uncertainties in MARXAN, there is no doubt that this approach may provide a powerful tool in conservation planning, decision-making and negotiation situations. The numerous solutions offered to one reserve problem, the measure of the selection frequency of sites and the ability to explore more complex problems quite quickly make MARXAN useful in evaluating trade-offs and the implications of future demands on land use on biodiversity conservation.

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CHAPTER 4

Opportunity costs and conservation planning: an evaluation of C-Plan and MARXAN

ABSTRACT

Conservation plans rely on the use of conservation planning software platforms and their associated algorithms to assist decision makers in determining options for achieving conservation goals and identifying priority conservation areas. This study compares two software platforms, C-Plan and MARXAN, highlighting their respective sensitivities in terms of inputs and planning parameters on the outputs generated. Understanding these sensitivities is crucial for correctly interpreting and using conservation outputs. C-Plan offers a user friendly, fast and fairly robust approach to evaluating the conservation importance of sites intuitively selecting appropriate areas. The sensitivity of outputs to input parameters are largely limited to the combination size and rules used in selecting areas. The iterative heuristic algorithm used does, however, have limitations when addressing certain spatial targets and minimising opportunity costs while achieving conservation targets. Better solutions for minimising opportunity costs are generated using simulated annealing, such as offered in MARXAN. Simulated annealing generates numerous solutions to a single problem while providing flexibility in the potential solutions. But the number of input parameters in MARXAN that requires setting and their respective sensitivities are more numerous. The impact and use of the cost threshold parameters, its balance with the conservation feature penalty factor, and generally the balance between different penalties in the objective function still require further investigation. The standardisation of some of MARXAN's planning parameters in CLUZ (an interface software that helps to integrate MARXAN into a GIS environment) is useful for providing a more user-friendly face to simulated annealing. Both software platforms have important roles to play in conservation planning. Deciding which to use when, will depend on a number of factors, but further documentation on best and current practice in MARXAN, the sensitivities of conservation plan outputs to input parameters, and inclusion of these sensitivities in training and capacity building exercises are required. At present the one platform offers some degree of uncertainty in dealing with trade-offs (C-plan) whereas the other (MARXAN) offers some degree of uncertainty in dealing with the input parameters when conducting trade-off assessments.

1. INTRODUCTION

1.1. Background

South Africa is one of the world leaders in regional conservation planning (Balmford 2003). Not only have a number of regional assessments to identify important priority areas for biodiversity conservation been conducted (Cowling et al. 1999; Cole et al. 2000; Cowling et al. 2003; Driver et al. 2003a; see special issue of *Biological Conservation* (volume 112, July/August 2003)), but South Africa's first National Spatial Biodiversity Assessment to identify national priorities is also completed (Rouget et al. 2005; Driver et al. 2005). These assessments followed the principles of systematic conservation planning which provide a rigorous and defensible framework for the incorporation of conservation principles into actual plans (Margules & Pressey 2000). The principles and advantages of systematic conservation planning have been well documented by scientists and practitioners across the world (for reviews see Margules & Pressey 2000; van Jaarsveld et al. 2003). Over the past two decades the principles of systematic conservation planning, which include quantitative target setting for spatially explicit biodiversity features, as well as complementarity, representivity and persistence, have set systematic conservation planning apart from other forms of planning (Pressey et al. 1993; Margules & Pressey 2000). Systematic conservation planning approaches make use of mathematical algorithms available in conservation planning software to assist in determining the conservation value of areas and selecting areas for inclusion in conservation networks.

The goal of biodiversity conservation can be expressed as the selection of areas that will efficiently and effectively represent all quantitative targets for biodiversity features at minimum cost, not only in terms of land area, but also management costs or opportunity cost for other land uses (Pressey et al. 1996; Margules & Pressey 2000; Faith and Walker 2002; Margules et al. 2002; Moore et al. 2004). Therefore, the basis of reserve selection algorithms is the minimisation of the area or other costs of the reserve network while achieving the defined conservation targets (Pressey et al. 1997; Possingham et al. 2000; Leslie et al. 2003; Stewart et al. 2003). Underlying this objective is that although biodiversity conservation objectives would maximise the area to be conserved, socio-economic and management constraints limit the land available (Possingham et al. 2000; Stewart et al. 2003). This problem was first defined by Kirkpatrick et al. (1983) as the "minimum representation problem". While minimizing the impact of reserve selection on alternative land uses has largely been limited to ensuring area efficiency, far fewer studies have directly incorporated opportunity costs for other land uses (defined as the forgone cost of choosing some other land use in favour of another - Faith & Walker 2002) or management costs into the area selection procedure. This is despite many of these land uses being of direct importance to human well-being, economies and development (Bohensky et al. 2004). The inclusion of opportunity or management costs into conservation planning makes reserve problems more complex, in that it reduces the flexibility of reserve solutions, and is restricted by the expression of biodiversity value and opportunity costs in different currencies (e.g. dollars, species, tons of food) or by the reliance of frequently unsatisfactory economic valuations to facilitate comparative analyses (En Chee 2004). But evidence suggests that conducting planning assessments that concurrently consider biodiversity conservation with human well-being and development, using plans that talk to one another, have increased options for better balanced regional trade-offs and for generating win-win scenarios (Gelderblom et al. 2002; Balmford 2003; Cowling & Pressey 2003; MA 2005). Interactive conservation planning software platforms are important tools to aid decision makers in exploring options, for achieving conservation goals and to identify high conservation value and priority areas. These software platforms continue to be valuable as the complexities of conservation planning problems grow. A number of different conservation planning software platforms exist, and can employ a variety of algorithms to solve reserve problems.

Algorithms used to solve reserve problems include optimization methods, heuristic approaches and methods using multivariate space (Moore et al. 2003; Pressey 2003). These approaches differ in the data they use, the analyses they conduct, their usability in interactive negotiations, and their ability to consider multiple objectives. For example, optimisation algorithms, although very powerful and capable of considering multiple objectives simultaneously and providing optimal solutions, have not been frequently used, although their use is increasing. This is as they tend to be prohibitively time consuming (except see Rodrigues & Gaston 2002), require investment in resources and expertise, and they can often fail when problems are non-linear (Leslie et al. 2003; Moore et al. 2003). Heuristic algorithms, although unable to guarantee optimal solutions are more frequently utilized in conservation planning and generally compare favourably with optimal solutions (Moore et al. 2003). Heuristic algorithms, in turn, can be divided into global heuristics, largely developed by operations researchers, and local heuristics largely developed by conservation researchers (Moore et al. 2003; Pressey 2003). Local heuristic algorithms have proved most popular in the conservation planning arena and are widely utilized in South Africa and Australia (Balmford 2003). This is despite them being unable to guarantee an optimal solution, which is quantitatively comparable to other solutions, and sometimes being outperformed by alternative algorithms (Pressey & Nichols 1989; Pressey et al. 1997; McDonnell et al. 2002). Local heuristic algorithms have also proved to be efficient, manageable and provide relatively robust and reasonable answers in most instances (Pressey et al. 1997; Possingham et al. 2000; Leslie et al. 2003). A characteristic of these algorithms is that they are based on the principle of complementarity. Complementarity is the area's relative contribution to attaining a particular conservation goal and seeks the most efficient solution by maximising the number of unrepresented biodiversity features with the addition of each site to the reserve solution (Sarkar & Margules 2002). These algorithms use a list of rules to select areas iteratively (stepwise selection by areas). Selection rules are defined by the user and usually relate to the biological value of a site, cost and/or spatial constraints. When solving between ties during the area selection process, constraints, such as opportunity or management costs and spatial constraints, are considered iteratively as secondary factors affecting the importance of the site for achieving conservation targets. Local heuristic algorithms provide simple and relatively rapid solutions that are easily communicable (Leslie et al. 2003; Moore et al. 2003).

Global heuristic algorithms include simulated annealing, neural networks and genetic algorithms. These algorithms work on the selection of sets of areas, can simultaneously consider multiple constraints and provide a useful quantitative estimate of the quality of their solutions. They have a long history and their performance and limitations have been well studied and defined (Rothley 1999; Rodrigues et al. 2000; Moore et al. 2003). Simulated annealing algorithms were based on the process of annealing metal and glass (Kirkpatrick et al. 1983) but have been successfully applied to conservation planning problems (Ball & Possingham 2000; Possingham et al. 2000; McDonnell et al. 2002; Leslie et al. 2003; Stewart et al. 2003). An objective function is used to quantify a particular set of sites selected. Units are included or excluded based on whether their inclusion or exclusion improves the overall objective function score. A strength of this approach is that it has a higher opportunity of reaching more optimal solutions and has outperformed simpler heuristic algorithms (Leslie et al. 2003). Simulated annealing algorithms attempt to find good sets of sites that meet a suite of user-defined biodiversity targets at minimal cost. They differ from other iterative approaches in that they allow the random selection of sets of sites early on in the process, which initially allow the algorithm to choose less than optimal sets of sites, and may allow for better selections at a later stage when the algorithm conditions becomes more strict (Ardron et al. 2002; Leslie et al. 2003).

One planning software platform, based on local heuristic algorithms, that has been used extensively for systematic conservation planning in South Africa is C-Plan (NSW 2001). C-Plan calculates the irreplaceability value of sites. Irreplaceability is a measure of the importance of one area, or the likelihood that an area will be needed for achieving specified conservation targets relative to all other areas (Pressey 1999; Ferrier et al. 2000; NSW 2001). It is an expression of an area's conservation value or options, in that it measures the flexibility with which an area can be substituted for another while still trying to achieve conservation targets (Pressey et al. 1993). Irreplaceability considers the complementarity of sites, and thus irreplaceability values must be recalculated with each change in the selection or exclusion of sites. C-plan facilitates the analysis of irreplaceability dynamically in a negotiation environment as decisions on conservation or development are made. Sometimes, the generation of a minimum set of areas that represent all biodiversity features under certain conditions is useful to the planning process. This minimum set is determined using a local heuristic algorithm. A sites irreplaceability score is frequently used as the first step of the selection procedure. C-plan has been widely used and has been proved very useful in the decision-making process (Pressey 1999).

Recently, there has been growing interest in the conservation planning software tool called MARXAN (Ball & Possingham 2002), which uses a simulated annealing algorithm to select sets of areas. The interest in this conservation planning software stems from its recent successful application to marine reserve problems. The algorithm is able to include a variety of spatial constraints and design considerations that assist in increasing the likelihood of reserve networks being biologically viable by considering the degree of fragmentation through a spatial contiguity component (Ball & Possingham 2002; McDonnell et al. 2002; Moore et al. 2004; Stewart et al. 2004). It is also able to find reserve solutions that outperform other heuristic approaches (Leslie et al. 2003). There has also been interest in the algorithms ability to consider costs and set cost thresholds (i.e. a threshold on the cost of selected sets of areas that should not be exceeded). The previous response of the conservation sector to incorporating site costs has largely revolved around the development of in-house iterative algorithms (Ferrier et al. 2000; Wessels et al. 2000; NSW 2001; Faith & Walker 2002). Simulated annealing allows the consideration of site costs simultaneously with the other criteria.

1.1.1. Aims and Objectives

The use and implicit assumptions and performances of different algorithms have been investigated in numerous studies (Possingham et al. 2000; Moore et al. 2003; Pressey 2003). Moreover, understanding the algorithmic approach, data requirements and sensitivities is crucial to providing a defensible and systematic conservation plan. In order to improve and document this understanding as it relates to C-Plan and MARXAN, this present study explores the relative abilities of these two conservation planning programs using data from the Gariep basin assessment of South Africa. The Gariep basin assessment formed part of the sub-global Southern African Millennium Ecosystem Assessment (SAfMA - Biggs et al. 2004; Bohensky et al. 2004). SAfMA was part of the global multi-scale ecosystem assessment (MA 2005) to investigate the relationship between ecosystem services and human well-being. The MA assessment explored the current conditions and trends of ecosystem services and their future capacity to continue delivering services in support of human well-being. The MA assessment also evaluated complex trade-offs inherent in the management of ecosystems for either biodiversity conservation or for the protection of ecosystem services they provide (Balvanera et al. 2001). The Gariep region was divided into 1110-quarter degree grid square sites and has 40 vegetation types and 134 species of special concern (including avian, mammal and amphibian species) of conservation importance. A site's opportunity cost is based on the tons of cereal production each site has the potential to produce in a year. Using these data, the relative merits and sensitivities associated with both C-Plan and MARXAN will be assessed in terms of:

- The data and software requirements
- Sensitivities of planning parameters with a description of the algorithms used
- General outputs and illustrations of the consequences of the inclusion of foregone opportunity costs for cereal production potential

This chapter does not attempt a true sensitivity analysis of the algorithms. It also does not attempt to prescribe or make recommendations about the setting of planning parameters for different conservation problems. The aim of this chapter is to illustrate the use of the two software platforms and to highlight the potential sensitivities associated with their use. These will require explicit examination but it is crucial that conservation planners consider them, especially in the case of the MARXAN as it is increasingly being employed.

1.2. Data and Conservation Objectives

1.2.1. Study area

Biodiversity and opportunity cost data for the Gariep basin from southern Africa is used to illustrate the sensitivities of reserve solutions to different algorithmic parameters in C-Plan and MARXAN. The Gariep basin has an area of 683600km^2 incorporating Lesotho and 60.7% of central South Africa and is formed by the Senqu-Gariep-Vaal river system (as well as two other primary catchments connected by major water transfer schemes: the Tugela river (or Thukela) and the Great Fish river (Bohensky et al. 2004). It is marked by a distinctive east-west precipitation gradient and contains all 7 of South Africa's biomes (defined by Low and Rebelo (1996)), although it is predominantly made up of the Savanna, Grasslands and Nama Karoo biomes. The region holds the so-called "bread-basket" of southern Africa contributing substantially toward meeting the cereal production needs of the human population, and explaining the substantial environmental impact of cereal cultivation (10.84 percent of the basin is cultivated).

The study area was divided into 1110 quarter-degree square (QDS) grid cells (15' x 15' ~ 700km^2; hereafter referred to as sites) (Figure 1). All data were generalised to a common resolution of a QDS to conform to the broader scale resolution of the species distribution data.

1.2.2. Biodiversity data and targets

Biodiversity feature data included distribution data on amphibians, birds, mammals and vegetation types (collated from Minter et al. 2003; Harrison et al. 1997; Freitag & van Jaarsveld 1995 and Keith 2004; Low & Rebelo 1996 respectively). Only species categorized as "species of special concern" (Rouget et al. 2005) being species either endemic to the region or threatened, according to the IUCN classifications of Critically Endangered, Endangered, Vulnerable and Near Threatened (IUCN 2001) and with >5% of their national distribution in the basin were included (Gaston & Rodrigues 2003; Rouget et al. 2005; but see Possingham et al. 2002). A total of 10 amphibian (2 endemic, 0 CR), 63 bird (0 endemic, 4 CR species) and 21 mammal (3 endemic, 3 CR) species were included. Species targets were set at a single representation of all species, except critically endangered species for which targets were increased to full representation. Vegetation targets were adjusted by the natural rarity of each vegetation type and a measure of threat within the vegetation type as calculated in Reyers (2003). Final vegetation targets range from 10 to 30% of the original extent of each vegetation type. Only remaining natural vegetation is considered in the achievement of vegetation targets.

1.2.3. Opportunity costs and targets

Opportunity costs for cereal production potential were calculated using a model developed for the Southern African Millennium Ecosystem Assessment (Scholes & Biggs 2004) that predicts total annual cereal production at a 5km x 5km resolution. The model is based on simple crop growth models, adjusted to observed production in South Africa as given by the Food and Agriculture Organisation statistics (FAO 2003) database, and restricted to cultivated areas (Scholes & Biggs 2004).

Cereal production is needed to feed the population living in the Gariep, and estimates of this demand will be important when evaluating the opportunity costs to cereal production of reserve networks. Three cereal production targets are used. A minimum cereal production target is determined by calculating the minimum daily calorie requirements from cereals for the population of the Gariep over a year (FAO & WHO 1998; Bohensky et al. 2004). Knowing the calorie content of cereal types (taken from FAO & IIASA 2000), this can be translated into tons of cereal needed over a year to meet the minimum food requirements of the Gariep population. Actual calorie intake can be much higher than this minimum and estimates of actual consumption rates of the different cereals types as a more accurate indication of cereal demand are used to calculate upper and lower cereal production targets (Nel & Steyn 2002). These three cereal targets are used to set cost thresholds above which the ability of the basin to meet the target is impaired

$$\text{Cost threshold} = \text{total cereal production potential} - \text{cereal target} \quad \text{(Eq. 1)}$$

Cost thresholds include a full threshold, which sets the total cereal production potential as the cost threshold (5620570 t/yr), and three others that subtract the cereal target from the total cereal production potential: high (2841742 t/yr), medium (138312.8 t/yr) and low (0.1 t/yr) cost threshold.

The South African national land cover database (Thompson 1996; Fairbanks et al. 2000) was intersected with vegetation data to determine the threat within vegetation types, the remaining natural vegetation, and the cultivated land in the Gariep basin.

The conservation objective is to represent all biodiversity features to their defined target levels and minimise the opportunity cost to cereal production potential. Below these datasets are used by C-Plan and MARXAN to illustrate the differences in the requirements, sensitivity and outputs between platforms.

2. ASSESSMENT OF C-PLAN AND MARXAN

2.1 Starting Requirements: Software and data

Both software platforms require that the user is familiar with geographical information and database systems. Both software platforms are fully functional stand-alone packages that can be run outside of geographical information system (GIS) software. However, in order to view the planning domain and facilitate spatial selection and assessment of sites, these software are used in conjunction with the geographical information system software ArcView (ESRI 1999). Both require the installation of an extension into ArcView to link the conservation planning software to the geographical information system interface. C-Plan links directly to ArcView. The interface between MARXAN and ArcView is an extension called CLUZ (Conservation Land-Use Zoning software – Smith 2004). CLUZ helps to integrate MARXAN into a GIS environment. CLUZ, however, does not offer access to all of the planning and simulated annealing parameters available in MARXAN. The interface opts for a high conservation feature penalty factor value, an adaptive annealing schedule, no post-selection algorithms and no cost threshold penalty option. CLUZ also sets a starting proportion of 20%, which is the percentage of the study area that is selected at random and from which the simulated annealing algorithm adds and subtracts sites. The influence of the starting proportion has not been tested explicitly in the literature, and could be substantial if the number of iterations run is not high enough. MARXAN input parameters that can be altered by the user in CLUZ is limited largely to the number of runs, number of iterations, the boundary length modifier and the setting of clump size target, where the target is the number of clumps of a particular conservation feature, which consists of all the sites that contain that feature within a specified distance from each other. Input files, saved as dbf's, can be imported into C-Plan and CLUZ and exported to create the input files necessary to run MARXAN. Without CLUZ, MARXAN cannot link directly with ArcView. CLUZ facilitates the same type of spatial viewing and selection and addition of sites as C-Plan does. Without it, selecting sites for inclusion, exclusion, reservation is a lengthier and less intuitive process, especially when dealing with stakeholders and decision-makers.

The first data requirement for both software platforms is that a geographically defined planning region be defined and that this planning region be subdivided into sites. Sites refer to any geographical area such as grid squares, water catchments, or vegetation type fragments. The software platforms then require attribute data on the biodiversity features within a planning region. Biodiversity feature data, commonly for biodiversity surrogates such as species or vegetation types, are recorded in terms of areas, occurrence, abundance, or probabilities. A quantitative target is set for each biodiversity feature.

Although neither platform runs in a spatially explicit fashion (i.e. there is no topology information used in the algorithms), MARXAN can incorporate information on the spatial separation and aggregation of patches through boundary length information containing a given biodiversity feature and requires a measure of the length of the boundary between all sites. This boundary measure can be in terms of the actual length or a cost value (Ball and Possingham 2000). Other data associated with sites includes cost, tenure and vulnerability of biodiversity to processes that threaten it. To summarise, the datasets used by both platforms are similar and thanks to CLUZ, both software platforms function usefully in geographical information systems (with the exception of the advanced parameters in MARXAN).

2.2 Sensitivity to Inputs

Two stages of the conservation planning process are the input of biodiversity and site data, followed by iterations of the algorithm to select areas that answer various reserve questions. Varieties of iterations are possible for the algorithms and depend on input parameters determined by the user. From the outset, when selecting data for use, setting targets and deciding on the area selection and conservation assessment procedure, conservation practitioners make subjective decisions. It is important to be aware of the sensitivities associated with these decisions. That is why it is crucial that conservation practitioners are explicit regarding the conservation objectives, feature targets, area selection procedures used, and the parameters utilised when using conservation planning software. This is essential to ensuring clear, systematic, repeatable and defensible conservation assessments. These two stages in conservation planning (input and algorithm parameters) are described below for both software platforms.

2.2.1. Data Inputs

While mathematical algorithms for reserve selection improve, the biodiversity data that feed into these algorithms and applications remain relatively poor (Possingham et al. 2000). Conservation planning software are sensitive to input data, although some may be more robust to certain data types than others (Possingham et al. 2000). Data inaccuracies, sampling bias, poor congruence of biodiversity surrogates and poor data resolution plague conservation plans the world over (van Jaarsveld et al. 1998; Reyers & van Jaarsveld 2000; Reyers et al. 2000; Reyers et al. 2001; Sarkar & Margules 2002; Williams et al. 2002; Wessels et al. 2003; Lombard et al. 2003). Ideally investment should be made into obtaining better data (Balmford & Gaston 1999) with focused and integrated effort from taxonomists to assist in rectifying current data problems (Golding & Timberlake 2003). But limited time, expertise and financial resources as well as increasing rates of habitat destruction make it an urgent task to select and conserve areas now. It is however critical that conservation planners understand the sensitivities of conservation algorithms to data type, quality and quantity (Possingham et al. 2000). More complex algorithms, such as simulated annealing, may not always provide a better solution, as they can be quite sensitive to the choice of inputs. Such limitations though, still require systematic examination (Possingham et al. 2000). In this study the biodiversity and site data were useable in both software, however the data are too coarse to feed directly into implementation – a weakness irrespective of the software used.

An additional, but equally influential input are the targets set for biodiversity features. Targets are the quantitative expression of the conservation goals of a region and ideally express the level of representation required for a biodiversity feature to persist with a given probability over a certain time period (Gaston et al. 2002). Conservation targets increase the reliability, repeatability and objectivity of systematic conservation planning, and are a fundamental, distinguishing aspect of this approach from other conservation planning approaches (such as scoring systems). They have a significant impact on the efficiency and effectiveness of resulting conservation plans, but their determination is no trivial matter as goals and values are not universal, biological patterns and processes are notoriously variable and complex at all levels of organisation, and there is little scientific basis that establishes what optimal targets may be (Soule & Sanjayan 1998; Williams 1998; NSW 2001; Sarkar & Margules 2002; Leslie et al. 2003; Stewart et al. 2003; Desmet & Cowling 2004). In addition to biodiversity feature targets for any particular group of biodiversity features, as described in Possingham et al. (2000), "determining the optimal balance of reserve clustering and separation to parameterize a simulated annealing algorithm requires detailed empirical data on species life history and/or the spatial distribution of catastrophes, which often do not exist". The setting of targets is the same for both platforms, although MARXAN does allow one to set the importance of target achievement, while C-Plan is primarily target driven (see next section). The differences between MARXAN and C-Plan are not significant based on the input data and the setting of targets, especially when employing CLUZ as an interface for MARXAN.

2.2.2. Input Parameters

I. C-Plan

a) Combination Size

There is a decided difference between C-Plan and MARXAN in terms of the algorithms and the number and type of planning parameters that require setting. Comparing the two, C-Plan has far few parameters and is relatively easy to use. Once the C-Plan input files have been entered, the irreplaceability of sites can be calculated and irreplaceability surfaces generated without any further input from the user. However, there is a parameter that is largely invisible, in that it is seldom defined explicitly in many conservation plans despite the fairly substantial influence it has on irreplaceability values. This is the combination size. Irreplaceability is measured through the generation of all possible combinations of areas and then checks which combinations of a particular size are representative of all features, where the number of component areas in any combination is the 'combination size' (Ferrier et al. 2000). It is recommended that the number of potential conservation areas (combination size) always be greater than the minimum number of sites required to achieve conservation targets (Ferrier et al. 2000). There is no mention of this parameter in the C-Plan manual and no literature regarding its impact on the calculation of irreplaceability. However, considering the impact it has on the number of irreplaceable sites at different combination sizes illustrated in Figure 1, care should be taken that the default combination size is not lower than the minimum combination size. This minimum is the combination size where the number of sites with an irreplaceability of 1 (i.e. number of irreplaceable sites) evens off (at 118 in this example). Figure 1 indicates how an irreplaceability surface with a combination size lower than the 118 will have more irreplaceable sites than one with a combination size higher than 118. Figure 2 illustrates this decrease with irreplaceability surfaces at three combination sizes.

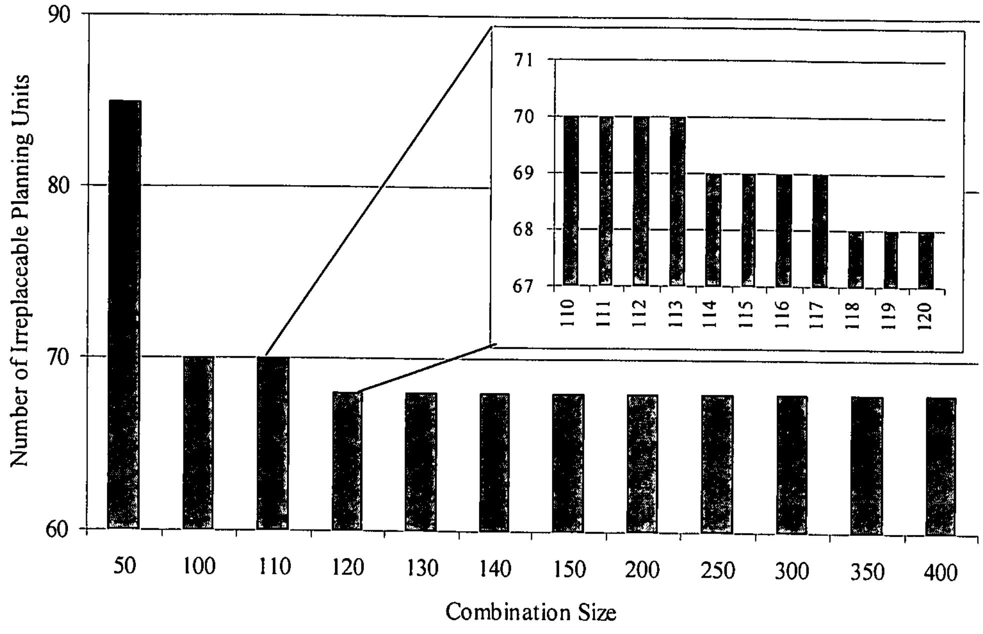

Figure 1. The number of irreplaceable planning units to achieving biodiversity feature targets in the Gariep basin at different combination sizes. The progressive reduction in the number of irreplaceable planning units up until the combination size of 118 is reached, is illustrated.

Figure 2. Irreplaceability of planning units (irreplaceability values from 0 to 1 with a value of 1 being totally irreplaceable) in the Gariep basin for representing all biodiversity features considered with a combination size of (a) 50, (b) 100 and (c) 118. The effect of the combination size on the irreplaceability surfaces is illustrated in the reduced irreplaceability values of planning units until the appropriate combination size is achieved where the number of totally irreplaceable planning units no longer declines.

b) Minimum Set

When it comes to the selection of a minimum set of areas for conservation that will fulfil a specific aim, namely the stopping criteria, there are a number of parameters that require setting. This minimum set is selected using the minset function in C-Plan. To select a minimum set of areas the minset function uses a set of rules by which sites are selected through an iterative search routine. The first rule is often based on the site with the highest irreplaceability value. If there is a tie between sites of equal irreplaceability, subsequent rules break ties until there are no more ties, or all the rules have been used. The higher the rule in the order, the more influence it has on the set of sites selected. Subsequent rules can include a rule that minimises the cost to an opportunity cost or threatening process, maximises the summed irreplaceability value or adds an adjacency constraint (Nicholls & Margules 1993). The user defines these rules but little literature exists on which rules to use when. After each selection C-Plan recalculates all values and a new site is selected following the same rules until the stopping condition is reached. The stopping condition can be a specified number of iterations, until all or a subset of biodiversity feature targets is satisfied or when a specified resource limit has been reached (NSW 2001).

Thus input parameters in C-Plan which impact on outputs are combination size (in irreplaceability calculations) and minimum set rules (in minimum set selection) and users need to be aware of the sensitivities associated with these parameters and that best practise is developed and published.

II. MARXAN

Prior to running MARXAN, a relatively large number of parameters need to be considered. The two main groups of parameters include the various conditions applied to the objective function and the solution method, which pertains to the annealing schedule.

a) Objective function

The reserve selection problem can be formulated mathematically in an objective function. An objective function provides a clear statement of the conservation objective so as to inform how selection of areas for reservation will proceed (Stewart and Possingham 2002). The objective function, C(x), is calculated as a combination of the cost of the sites selected and penalties for violating various criteria. The inclusion of penalties is largely optional, but one that is not optional is the penalty incurred if conservation feature targets are not fully represented. This penalty is based on the cost and boundary length of the sites that would be required to fully represent the conservation feature targets that are not achieved. No penalty is incurred if all conservation feature targets are met. The application of additional penalties allows the user more control over the spatial and cost implications of the reserve solutions.

For instance, if a cost threshold is set, reserve solutions that exceed this site cost threshold are penalized, or if spatial fragmentation targets are set, not meeting some of these targets will also incur a penalty. The overall penalty value is the sum of these individual penalties. The objective function can be summarised as follows:

$$C(x) = \sum_{\text{Sites}} \text{Cost} + \text{BLM} \sum_{\text{Sites}} \text{Boundary} + \sum_{\text{ConValue}} \text{CFPF} \times \text{Penalty} + \text{Cost Threshold Penalty}\ (t) \qquad \text{(Eq. 2)}$$

i) Cost

Cost is the sum of some cost measure: in terms of the area used, the economic cost or the opportunity cost for other land uses, of each of the sites within a selected reserve system. The ability to include opportunity costs is largely limited to this cost variable, although there is an option of replacing the boundary length with an opportunity cost. This is explained below. In our example dataset, the cost of the sites is considered the cereal production potential in tons per year.

ii) Boundary length

The boundary length is the boundary that the sites in a reserve solution share with unprotected sites. This can be the actual length of the boundary between two sites, but could be any value and could be related to some other cost value of the sites. For instance, sites with a lower cost (shorter boundary length) would be included in the reserve solution before ones with a high cost (longer boundary length).

iii) Boundary Length Modifier (BLM)

The constant BLM is the boundary length modifier, which converts the reserve system cost and its boundary length into a common currency and determines the relative importance placed on minimising the boundary length relative to minimising cost (Leslie et al. 2003; Stewart et al. 2003). A BLM of 0 excludes the boundary length from the objective function. A BLM higher than 0 increases the degree of connectivity and clumping between selected sites. This invariably reduces the area efficiency of the solution. A number of studies have investigated this relationship (Leslie et al. 2003; Stewart et al. 2003). As the BLM increases, the degree to which area is weighted against boundary length decreases (Leslie et al. 2003; Stewart et al. 2003). Stewart et al. (2003) suggests a threshold of between 1 and 10 where it becomes more important for the BLM to be minimised than area. If the objective is to minimise area with some clustering their study suggests a BLM of just below 1, as above 1 there is a rapid increase in the area required. Other studies also suggest that an appropriate balance between the total area and clustering with the BLM parameter can be achieved with values of between 0.5 and 1 (Possingham et al. 2000; Ardron et al. 2002).

iv) Conservation Feature Penalty Factor

Summed for all conservation features, the next component of the objective function inflicts a penalty if conservation features are not adequately represented. The penalty term is calculated in terms of cost and boundary length. It is approximately the additional modified boundary and cost of adequately representing all conservation features that are not adequately represented in the reserve system (Ball & Possingham 2000). This penalty is multiplied by the conservation feature penalty factor (CFPF), which is a weighting factor that determines how important it is that a particular conservation feature is adequately represented in a reserve selection (Ball & Possingham 2000). Certain conservation features, such as critically endangered species, can be given high conservation feature penalty factors to ensure that their targets are achieved (McDonnell et al. 2002; Stewart et al. 2003). To illustrate this, and other parameters, the summary results of reserve solutions from nine planning scenarios are assessed (Table 1). Eight of the planning scenarios are made up using four cost thresholds (full, high, medium and low) that are tested at two different cost threshold control parameters (lenient and strict). Cost thresholds and their control parameters will be explained in the next section. The ninth planning scenario has no cost threshold set. These nine planning scenarios are run using two different conservation feature penalty factors in selection procedure 1 and it is the difference between these two penalty factors that is initially compared.

With combination conservation feature penalty factors, critically endangered species are given a factor value of 10000, while all other have a factor value of 1000. Table 1 illustrates that this lower factor value is not high enough to outweigh penalties incurred when the reserve problem becomes more costly to cereal production at low cost thresholds; this means that at low cost thresholds some conservation feature targets are not fully represented. However, all critically endangered species were fully represented, as their penalty factor was high enough to outweigh other penalties. In the second example, all conservation features were assigned a high factor value of 10000 and all conservation feature targets are fully represented in all planning scenarios.

There is no standard approach for determining the size of the conservation feature penalty factor. Values much greater than 1 are more likely to guarantee representation of conservation features (Ball & Possingham 2000). Ardron et al. (2002) also suggest that this penalty will vary to balance with the cost threshold penalty if this optional threshold is set. To ensure conservation feature target achievement, the conservation feature penalty factor must be high enough to outweigh any other penalties incurred for ensuring their representation. It is important to remember that unlike a minimum set algorithm in C-Plan, which aims to achieve all targets, MARXAN does not have to do this. As illustrated, if the conservation feature penalty factors are too low, not all conservation feature targets will be met. The full representation of conservation feature targets may be influenced by the length of time allowed in finding a solution and in cases where opportunity costs and cost thresholds are included.

v) Cost threshold and cost threshold control parameters

The cost threshold penalty is an optional penalty applied if a cost threshold related to the cost measure assigned to sites is set. The objective function is penalized whenever the sum of the cost measure increases above the cost threshold value. This penalty is a function of the cost of the reserve system and depending on the algorithm used to select sites, it will change as the algorithm progresses (Ball & Possingham 2000). The cost threshold penalty depends on the degree to which the cost threshold has been exceeded and is determined by two cost threshold control parameters as follows:

$$\text{Cost Threshold Penalty} = \text{Amount over Threshold x } (Ae^{Bt} - A) \qquad \text{(Eq. 3)}$$

where t is the proportion of the run (from 0 to 1), A controls the final value and B controls how steep the curve is (Ball & Possingham). Setting a high A gives a high penalty for any excess of the cost threshold, while a low A might allow some excess of the cost threshold. Thus, these two control parameters can be set to penalize any excess of the threshold more or less strictly, but requires some experimentation to set. As already introduced, Table 1 gives the results of nine planning scenarios that differ with respect to the cost threshold applied and its control parameters. Considering only the results in selection procedure 1, the differences in the cost of the reserve solution, the number of sites and the number of missing conservation features are evaluated in these planning scenarios.

The full and high cost thresholds are high enough to ensure that reserve solutions meet all conservation feature targets without exceeding the thresholds. The summary results at these thresholds under both conservation feature penalty factors and with lenient and strict cost threshold penalty parameters are very similar. The foregone cereal production potential for all solutions is 18.5% and the area required is just under 21% of the Gariep basin. This is not the case at medium and low cost thresholds, where all solutions exceed the set cost thresholds and it is not always possible to achieve all of the conservation feature targets within the specified cost threshold constraints. At these lower cost thresholds, it is the cost threshold control parameters that influences the impact of other parameter settings such as conservation feature penalty factors. Strict control parameters will penalise reserve solutions that exceed the cost threshold quickly and this penalty will outweigh the penalty for not representing all conservation feature targets if the conservation feature penalty factor is not high enough. Unusually, the cost of reserve solutions increases at lower cost thresholds, except where conservation feature targets are not fully represented. This is unusual because at lower thresholds it might be expected that the reserve solution would be as low as it can possibly get without under-representing conservation feature targets. This is not the case, especially when it is considered in relation to the reserve solution generated when no cost threshold is applied. The no cost threshold solutions have a lower cost but do require a higher number of sites. Even with the full cost threshold, which cannot be exceeded, the use of the cost threshold function has an impact on the reserve solution generated.

At its most basic, the objective function score can be the summed cost of the sites and a penalty for any biodiversity feature targets that are not represented. Including the boundary length, any spatial constraints or a cost threshold penalty are optional. Objective function parameters such as the conservation feature penalty factor, boundary length modifier and cost threshold penalty have significant impacts on the outputs in a conservation plan. Some work has been done on appropriate boundary length modifier and conservation feature penalty factor values and some recommendations exist (Possingham et al. 2000, Ardron et al. 2002, Leslie et al. 2003, Stewart et al. 2003). However, the impacts of the cost threshold penalty have not been tested in the literature and results from chapter 3 question the impacts of setting a cost threshold. The values and interactions between the penalties of conservation features and cost thresholds can have significant consequences for reserve selection and require more analysis to provide recommendations for users. In addition to the parameters of the objective function, the selection of sites, for which the objective function is determined, can be chosen using different optimization algorithms. This study focuses on the use of simulated annealing to select sets of areas as potential reserve solutions.

b) Simulated annealing

Simulated annealing is an optimisation algorithm that is based on three main elements, iterative improvement, initial random acceptance of bad moves and repetition (Ball & Possingham 2000, Possingham et al. 2000, Ardron et al. 2002). The first element is the iterative improvement of an initial reserve solution. A site is selected at random and depending on whether it improves the objective function, it is either included (if it is not yet included in the reserve solution) or excluded (if it is already in the reserve solution). Iterative improvement focuses on accepting changes that reduce the cost of the reserve solution, but in order to avoid local minima, a stochastic acceptance of bad moves is included. This is the second element of simulated annealing. The probability of 'bad moves', roughly defined as the inclusion or exclusion of a site that increases the cost of the reserve solution, being accepted is determined by the annealing schedule (Ball & Possingham 2000; McDonnell et al. 2002).

i) Annealing Schedule

The annealing schedule is analogous to the physical process of heating and cooling metals to obtain a strong crystalline structure and is determined by the acceptance function. The acceptance function, which is defined by an initial temperature, number of temperature decreases and final temperature, determines the acceptance of 'bad' moves. The temperature starts high and decreases during the algorithm. While the temperature is high, 'bad moves' have a higher probability of being accepted, but as the temperature decreases, the likelihood that a bad change is accepted decreases. The process of excluding and including sites is repeated a number of times and is determined by the number of iterations set. The algorithm completes a user-defined number of iterations (at each iteration a site is randomly chosen and accepted or rejected), which determines how long the annealing algorithm will take on each run (Ball & Possingham 2000). A higher number of iterations increases the chances of finding a lower solution. The acceptance function determines how much of that time bad moves are accepted (how quickly the temperature decreases to a point where only good changes are accepted).

A user-defined acceptance function (fixed annealing) is optional and adaptive annealing can be selected where the algorithm will choose the acceptance function parameters (Ball & Possingham 2000). It is suggested that a fixed annealing schedule will generally produce better results more quickly than an adaptive annealing schedule (Ardron et al. 2002; Ball & Possingham 2000). The fixed annealing schedule can only be arrived at experimentally and will be different for every conservation planning problem. But its determination requires great care and patience, and a good fixed annealing schedule can be difficult to determine, as only a number of 'rules of thumb' exist for this (Kirkpatrick 1983; Lundy & Mees 1986; McDonnell et al. 2002).

ii) Algorithms used in combination with simulated annealing

At the point that the temperature is lowest and only good changes are accepted, other area selection algorithms can be used in combination with simulated annealing to refine the initial reserve selection chosen by the simulated annealing algorithm. One such algorithm is the summed irreplaceability heuristic, which acts to reduce redundancy by determining how essential each site is towards meeting conservation targets for each feature and improves the final reserve solution by ensuring that both rarity and richness are accounted for (Ardron et al. 2002). Another algorithm is normal iterative improvement, which is a recommended follow-up algorithm to simulated annealing, checks each site for its utility in the final reserve solution and ensures that a local minima is reached (Ball & Possingham 2000; Ardron et al. 2002). There is little available literature to guide users in the selection and use of these additional algorithms in conservation planning problems. To illustrate the influence of these algorithms on reserve solutions, two selection procedures are compared in Table 1. In selection procedure 1, the simulated annealing algorithm is followed by summed irreplaceability heuristic and normal iterative improvement, while in selection procedure 2 the simulated annealing is followed by normal iterative improvement.

Considering the same nine planning scenarios, we compare summary results of the two different selection procedures. The lower number of sites selected in reserve solutions in selection procedure 1 suggest that there is a degree of redundancy in the set of sites selected in selection procedure 2 which does not use the summed irreplaceability heuristic. Unlike the summary results from selection procedure 1 already evaluated, the cost of the reserve solutions in selection procedure 2 decreases as cost thresholds become lower and more difficult to achieve. Therefore, the stricter cost threshold control parameters and easily exceeded cost threshold guide the algorithm in selecting more sites but with lower cereal production potential. Overall however, selection procedure 1 still generates reserve solutions that have a lower cost to cereal production and require fewer sites. The distinction between the two selection procedures is not very evident when no cost threshold is applied as median and standard deviation values for cost and the number of sites are very similar and reserve solutions are significantly correlated (Spearman $R = 0.90$, $df = 1109$, $p<0.05$).

Table 1. Summary of the best reserve solutions generated using four cost thresholds for cereal production potential (full = 560570, high = 27814, medium = 138312.8, low = 0.1) under two cost threshold control parameter scenarios (lenient and strict). Reserve solutions were generated using two selection procedures, the first using simulated annealing algorithm to select sets of areas followed by summed irreplaceability heuristic and normal iterative improvement (selection procedure 1) and the second using simulated annealing followed by normal iterative improvement (selection procedure 2). Two conservation feature penalty factors (CFPF) are used in the selection procedure 1: high CFPF gives all conservation features a penalty value of 10000, and combination gives all critically endangered conservation features a penalty factor of 10000 and the other features 1000. The average and standard deviation over 100 reserve solutions are given below each value.

Scenario	*Cost Threshold*	*Selection procedure 1 High CFPF*			*Selection procedure 1 Combination CFPF*			*Selection procedure 2 High CFPF*		
		Cost %	*No. missing features*	*No. sites*	*Cost %*	*No. missing features*	*No. sites*	*Cost %*	*No. missing features*	*No. sites*
	None	16.11	0	404	16.02	0	423	16.01	0	418
		16.69 ± 0.31	0	409.09 ± 11.32	16.67 ± 0.33	0	410.72 ± 10.85	16.66 ± 0.31	0	410.09 ± 12.03
Lenient	Full	18.5	0	225	18.5	0	226	25.33	0	275
		18.66 ± 0.11	0	229.61 ± 2.71	31.26 ± 2.21	0	284.97 ± 5.39	31.6 ± 2.02	0	285.88 ± 5.88
	High	18.5	0	230	18.5	0	230	26.03	0	271
		18.65 ± 0.1	0	229.45 ± 2.66	30.96 ± 2.11	0	284.22 ± 5.47	31.57 ± 2.09	0	285.7 ± 5.67
	Medium	25.28	0	245	23.94	0	241	24.96	0	285
		30.84 ± 2.13	0	252.46 ± 3.82	26.88 ± 1.97	0	277.98 ± 5.44	31.35 ± 2.12	0	285.17 ± 5.86
	Low	25.3	0	247	22.02	0	238	25.38	0	268
		31.34 ± 2.15	0	253.46 ± 3.69	26.37 ± 1.88	0	278.82 ± 5.64	31.18 ± 2.03	0	284.78 ± 5.95
Strict	Full	18.5	0	232	18.5	0	234	26.36	0	279
		18.66 ± 0.1	0	228.9 ± 2.3	30.96 ± 2.1	0	283.75 ± 4.82	31.7 ± 2.06	0	285.68 ± 5.81
	High	18.5	0	232	18.5	0	228	25.57	0	279
		18.65 ± 0.1	0	229.13 ± 2.27	30.61 ± 2.06	0	283.31 ± 6.07	31.46 ± 2.11	0	285.83 ± 5.55
	Medium	18.55	0	234	8.85	17	167	18.75	0	272
		21.82 ± 1.32	0	240.61 ± 3.38	8.85 ± 0	17 ± 0	200.37 ± 4.68	21.7 ± 1.34	0.28 ± 0.45	273.15 ± 5.46
	Low	24.49	0	245	8.85	17	164	18.69	0	270
		29.07 ± 2.1	0	249.97 ± 3.78	8.85 ± 0	17 ± 0	201.11 ± 4.56	21.75 ± 1.33	0.26 ± 0.44	273.43 ± 5.31

iii) Runs: Repeating the process

The final element of simulated annealing is that the algorithm repeats this process a user-defined number of times. Each repetition is one run. The user determines the number of runs and the best solution out of all runs is determined based on the lowest objective function score. The number of runs and the number of iterations are important parameters as they set the amount of time that the algorithm spends looking for a good solution and how many times it looks. The more opportunity the algorithm has to find a good solution the better but the running time increases linearly with the increase in either of these parameters (Stewart et al. 2003). In some cases, an increase in iterations may be more important than an increase in runs in finding better solutions but this appears to depend on the planning scenario (Stewart et al. 2003). Also at some point, the improvement of the solution generated with an increased number of iterations and runs will be small in comparison to the time taken to complete them.

CLUZ makes several of these decisions unnecessary by opting for a default high conservation feature penalty factor, no cost threshold option, adaptive annealing and no post selection algorithms. By limiting the parameters that the user must define CLUZ provides a more user-friendly face to MARXAN. When not using CLUZ, this study recommends that the user understand what MARXAN is capable of and have their objectives and spatial design requirements explicitly defined prior to its use. This will limit needless 'playing' with unnecessary planning parameters. However, while exploring different input parameters, we recommend the use of an adaptive annealing schedule in simulated annealing be followed perhaps by an iterative improvement algorithm. We propose that a minimum of 1000000 iterations is reasonable for exploring solutions and that it is rather the number of runs that is lowered to explore solutions within a faster time period. The setting of the boundary length modifier can be guided by existing literature and through experimentation. With regards to the penalty parameters, we recommend that a high conservation feature penalty factor, of at least 10000 be set, the proportion of target met before a conservation feature is considered missing be high (greater than or equal to 0.95) and that the cost threshold penalty be used with care. It must be noted though that several of these parameters are data and context dependent and there is a large amount of variability in the parameters used. From this assessment of input parameters MARXAN is far more complex and parameter dependent than C-Plan and therefore requires careful use and planning.

3. OUTPUTS

Both conservation planning outputs generate two outputs: a measure of the importance of sites to achieving a reserve solution (a measure of conservation value) and a minimum or best set of sites to achieve the reserve solution.

3.1. Measures of conservation value of sites

In terms of a sites conservation value, C-Plan uses a powerful statistical approach to calculate irreplaceability (Ferrier et al. 2000). Irreplaceability indicates the likelihood that a site will have to be included in a conservation network in order to achieve a set of defined conservation feature targets (Pressey 1999). A site that is totally irreplaceable, such as a site that holds the only occurrence of a conservation feature, must be included into a conservation network no matter how it is designed if all conservation targets are to be achieved. If the site becomes unavailable for conservation, then the options for achieving all conservation feature targets is reduced, thereby giving a measure on the extent to which options are reduced when sites become unavailable for conservation (Pressey 1999). Irreplaceability varies from 0 to 1 with 1 being totally irreplaceable.

In MARXAN, the random element involved in selecting sets of areas using simulated annealing will mean that no two runs are likely to produce exactly the same results (Ball & Possingham 2000; Ardron et al. 2002). This provides planners with a number of solutions to a reserve design problem and presents a certain amount of flexibility for finding reserve solutions that meet multiple objectives. The results from all runs help to discern general trends in the selection process, indicating the frequency with which sites are selected. Both this measure and the irreplaceability calculated in C-Plan are driven by a goal, inform the user of options for replacements and provide a useful way of exploring the conservation value of sites in that it provides a measure of the relative importance of a site (Ball & Possingham 2000; Day et al. 2002; Leslie et al. 2003). However, in C-Plan the goal is related solely to the biodiversity value of the sites and not all sites selected with high frequency in MARXAN, which is based on all the data in the objective function, are irreplaceable in the same sense as C-Plan's irreplaceability (Pressey 1999; Ferrier et al. 2000; Ardron et al. 2002, Lieberknecht et al. 2004). MARXAN does however use the term *irreplaceability* in reference to this measure, which seems to cause unnecessary confusion due to its differences from irreplaceability used in C-Plan. Other studies have used different terms to describe this measure (Ardron et al. 2002; Day et al. 2002). Ardron et al. (2002) refer to sites with high frequencies of selection as having high *utility*, in that they represent areas that seem to be useful in the development of a reserve solution that best meets defined objectives. Day et al. (2002) refer to the *flexibility* of a site, with reference to its flexibility to being replaced by another site in achieving the required objectives. Stewart et al. (2003) provide a method of calculating a meaningful measure of whether a site is selected more often than at random in calculating the number of times a site is selected as part of a reserve solution out of the total number of reserve solutions generated. They refer to this measure as the *summed irreplaceability* of sites.

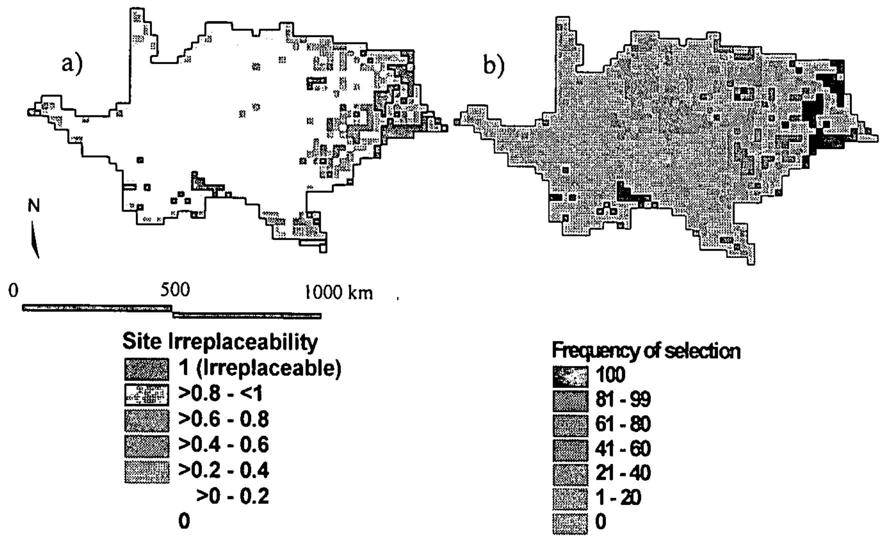

Figure 3. Irreplaceability of planning units calculated in C-Plan (a) and the selection frequency of planning units calculated in MARXAN (b) based solely on the conservation features they hold.

We refer to this measure as the *selection frequency* of a site as it provides the simplest and clearance description of the measure. It is however evident that some standardisation of terminology is necessary.

Figure 3 illustrates the irreplaceability of sites to representing biodiversity feature targets from C-Plan and the selection frequency of sites for meeting biodiversity feature targets from MARXAN. In this example where there are no spatial constraints and no site cost is included, the site irreplaceability and selection frequency are significantly correlated (Spearman R = 0.55, df = 1109, $p<0.05$). There are an equal number of irreplaceable sites and sites with a 100% selection frequency, but there are more sites that are not selected at all during the MARXAN runs (80 sites) than there are sites with 0 irreplaceability in C-Plan (50 sites).

Figure 4 illustrates the selection frequency in MARXAN when sites are assigned an opportunity cost, of cereal production potential, but no cost threshold penalty is applied (figure 4a), and when a cost threshold is applied to the objective function (figure 4b). The algorithm now attempts to maximise feature representation and minimise cost of sites. There is an evident increase in the selection frequency of sites in the western half of the basin, which has lower cereal production potential, and overall 85 sites are selected in 100 percent of the runs while 300 are not selected at all. Comparing the selection frequency of the solutions with no cost threshold penalty set to the irreplaceability values of sites from C-Plan, there is no significant correlation (Spearman R = 0.05, df = 1109, $p>0.05$). However, this is different for the selection frequency for solutions that have a cost threshold set. The cost threshold is based on the cereal production needs of the Gariep basin. Exceeding this cost threshold will therefore reduce the ability of the Gariep to meet these cereal demands. As in the solutions in figure 4a, the algorithm tries to maximise the feature representation and minimise cost of sites but with the proviso that a penalty will be attached if the cost threshold is exceeded. The selection frequency map (figure 4b) illustrates the reduced flexibility in finding such a solution. The larger number of the sites selected in 100 percent of the runs (191 sites) and the increased number of sites not selected at all (722 sites) is evidence of this. This selection frequency is significantly correlated with irreplaceability of sites from C-Plan (Spearman R = 0.57, df = 1109, $p<0.05$). However, the large number of sites selected 100% of the time may influence this result.

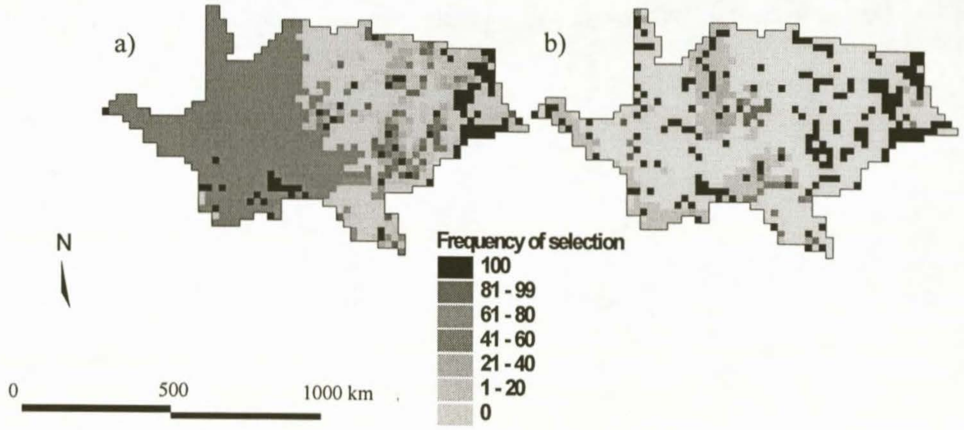

Figure 4. Selection frequency of planning units calculated in MARXAN when the planning unit cost, in terms of the planning units cereal production potential, is included but no cost threshold is applied (a) and when a cost threshold, equal to the full cereal production potential of the basin, is applied to the objective function (b). The threshold applied cannot be exceeded and therefore should not penalise the objective function.

These examples are given as an illustration of an important distinction between C-Plan's site irreplaceability and MARXAN's site selection frequency. C-Plan's site irreplaceability is based solely on the importance of the site to achieving biodiversity feature targets and, although they may be significantly correlated when no costs information is considered, the correlation is not incredible strong. Selection frequency can on the other hand indicate the importance of sites for achieving multiple objectives. These multiple objectives may include site costs, cost thresholds or spatial constraint options available in MARXAN. These additional objectives are not considered in the calculation. Caution should be taken when referring to selection frequency surfaces as 'irreplaceability' surfaces in order to avoid misinterpretation for those accustomed to site irreplaceability surfaces from C-Plan. C-Plan is useful if the user is largely interested in exploring solutions that achieve biodiversity targets, and although this can also be done in MARXAN, MARXAN does not provide the site irreplaceability values of sites that many conservation planners and managers have more experience in interpreting. MARXAN however, provides more flexibility and power in evaluating targets and the impacts of costs on sites, which is useful for trade-off assessment.

3.2. Reserve solutions

Using the site irreplaceability values of the sites alone or in combination with other data, C-Plan selects a minimum set of sites for the planning scenario dictated by the heuristic rules determined by the conservation planner. Figure 5a illustrates a minimum set of sites considering only the irreplaceability value of the sites in their selection. The selection is only stopped once all biodiversity feature targets have been achieved. Figure 5b illustrates the set of sites selected in C-Plan when the cereal production potential value of the sites is considered in the step-wise selection of sites. When there is a tie between two sites of equal irreplaceability value, a lower cereal production potential is used as a tie-breaking rule in the selection procedure. However, while these clearly predictable steps in deriving this solution are attractive, it is likely that alternative approaches could produce better results (Possingham et al. 2000; Moore et al. 2003). Using the simulated annealing algorithm, a reserve solution for biodiversity feature target representation without the inclusion of planning cost is illustrated in Figure 5c. If the site cost in terms of cereal production potential is included there is a dramatic increase in the number and distribution of sites selected (Figure 5d). This changes again when a cost threshold is applied. The reserve solution in Figure 5e has a full cost threshold, in other words the cost threshold cannot be exceeded or the objective function penalised, but still the number of sites decreases and their distribution is not as heavily biased towards the western half of the basin.

The representation of biodiversity feature targets is the primary objective in these solutions and is achieved in all cases (Table 2). Each solution has a different set of sites selected and thus incurs different opportunity costs to cereal production potential. The reserve solution that incurs the lowest cost to cereal production potential is the set of sites selected by simulated annealing when the cost of the sites is considered. However this solution is considerably more area intensive. Many sites in the low cereal production areas of the western half of the basin are selected because their selection does not increase the cost of the solution (i.e. they have no cereal production potential) and not because they contribute greatly towards conservation targets. These solutions do not provide practical answers as unnecessarily selected land may have value to other land uses. The C-Plan selection, which iteratively achieves targets and tries to minimise cost, is the next lowest impact on cereal production. The reserve solution generated in C-Plan considering the site irreplaceability of the sites only selects the smallest number of sites but has a higher cost to cereal production potential. The MARXAN solution that considers only the representation of conservation features selects a slightly larger number of sites but has a higher impact of cereal production. The reserve solution generated with the application of a cost threshold in MARXAN has a lower cost efficiency than that generated when no cost threshold is applied. The poor performance of the MARXAN solution with a cost threshold set is an unusual result and problematic in that it raises questions about the application of the cost threshold penalty when trying to minimise opportunity costs. The cost threshold set in this case is set at the total cereal production potential of the basin and cannot be exceeded and therefore would not penalise the objective function at any point. And yet it has some constraining effect that hinders the selection of the most cost efficient solution. The reason for such a result requires further clarification and could relate to anomalies of the software or algorithm. Cost thresholds have however not been used in other studies and the basis for comparison is limited.

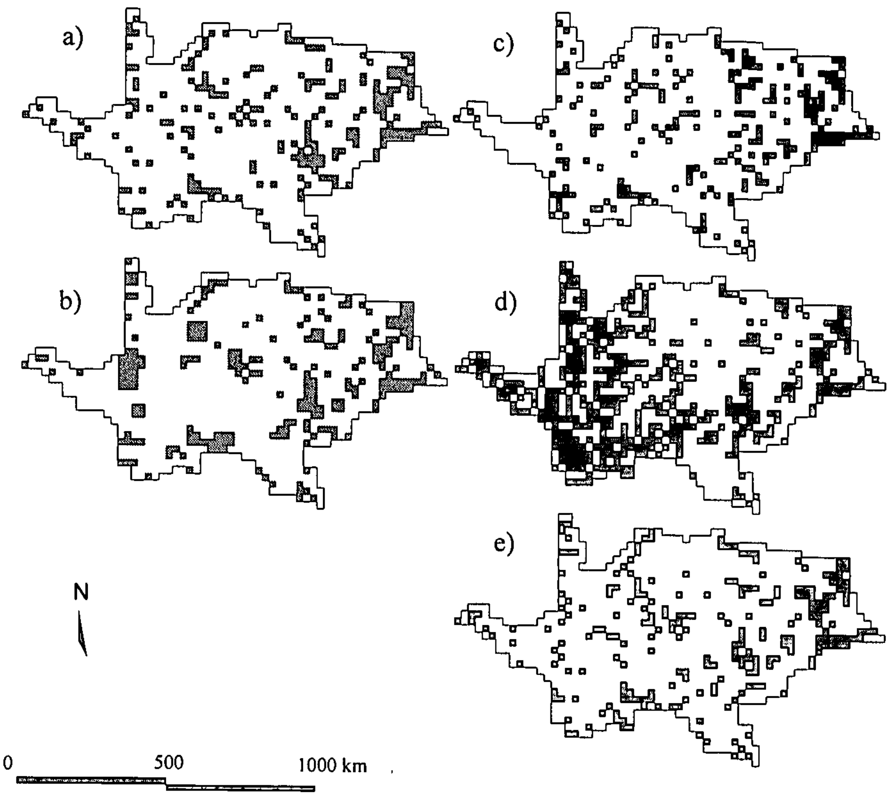

Figure 5. Best area selections from C-Plan (a-b) and MARXAN (c-e). The irreplaceability of biodiversity features is shown in a), which was then used to iteratively select the planning units in b) with the cost of planning units as a secondary rule in the minimum set. The areas selected in MARXAN when there is no planning unit cost (c), when no cost threshold is set but the cost of the planning units is taken into account (d) and finally, the areas selected when a cost threshold is set (e). All solutions meet all biodiversity feature targets and solutions with lowest to highest cost to cereal production are as follows d), b), e) a) and c).

Table 2. Summary of results for reserve solutions selected using two different planning software algorithms and three different conservation objectives. Results are given in terms of cost to cereal production potential, representation of biodiversity feature targets, number of sites required and the overlap with sites of highest cereal production potential.

Conservation objectives considered in area selection	*Software*	*Cost %*	*No. missing features*	*No. sites*	*No. sites in top 10% cereal production*
a) Biodiversity feature target representation	C-Plan	17.69	0	218	19
b) Biodiversity feature target representation and minimisation of cost to cereal production potential	C-Plan	16.93	0	235	14
c) Biodiversity feature target representation	MARXAN	24.07	0	228	22
d) Biodiversity feature target representation and minimisation of cost to cereal production potential	MARXAN	15.93	0	404	13
e) Biodiversity feature target representation and minimisation of cost to cereal production potential, with a penalty for exceeding a cost threshold	MARXAN	18.50	0	232	18

Table 2 also shows the number of sites in these selections that are also some of the 10% highest cereal producing sites. Planning scenarios that try to minimise cost have fewer of these high cereal production sites in their reserve solutions. In reserve solutions that attempt to minimize the cost to cereal production, those sites that still overlap with areas of high cereal production potential seem unlikely to be avoided without reducing the potential to fully represent all conservation features. The five reserve solutions highlight the benefit of including cereal production potential as a cost into the selection process where a reserve solution that has fewer sites that overlap with high cereal producing sites is found. Reducing this overlap reduces the need to make trade-offs and solve conflicts in these areas. Solutions that do not reduce the costs and thereby conflicts could indicate a greater number of areas that seemingly require prioritisation and urgent conservation action, when in fact this would be unnecessary.

Rule-based heuristics of C-Plan are limited to one solution if the starting rule stays the same, while different reserve solutions generated in MARXAN provide some flexibility in planning options (Ardron et al. 2002). In MARXAN, due to the random element in the selection of sites, repetition of the process could likely generate a different solution from other best solutions (dependent on how close the solution is getting to the optimal solution and how constrained the options are). This, in addition to the selection frequency over a number of runs, indicates the degree of flexibility and different options available for reserve solutions under particular scenarios (Ardron et al. 2002). This flexibility is inherent in the selection frequency but the generation of a number of possible reserve solutions with simulated annealing aids the understanding of the different options available and may help break out of certain constraining area selection patterns. It would therefore appear that the reserve selection outputs of MARXAN are more useful for trade-off and conflict assessments. In addition, the ability to investigate different spatial constraints and targets in MARXAN make the software platform capable of exploring many different reserve solutions and is thus a powerful and useful conservation planning tool.

4. DISCUSSION

Reserve selection algorithms have been used and developed over the last two decades and have greatly enabled conservation planners in solving large, complex conservation problems. However, it is also a trend that more complex and technical algorithms are being used to solve increasingly large and complex conservation problems. The use and interpretation of these algorithms requires significant technical expertise, in addition sometimes to specific, fairly extensive datasets and outputs (Roberts et al. 2003a, b). The use and interpretation of these software platforms requires two levels of capacity. The first is the capacity in implementing agencies to interpret and use the products of a conservation plan.

Several products and projects have been developed to empower the users of conservation plan products in a bid to ensure mainstreaming of biodiversity conservation objectives into other development sectors and facilitate conservation action at different governmental and management levels (Pierce et al. 2002, Driver et al. 2003b). The second form of capacity can be developed in the implementing agencies or other conservation agencies. This capacity is more technical in nature requiring geographical information systems, database and conservation biology expertise. These two sets of expertise ideally need not sit in the same agency or person.

Conservation planning software platforms like C-Plan, MARXAN and CLUZ make algorithms easy to use and when linked with geographical information systems, results are illustrated spatially in a manner that facilitates the selection of areas and benefits negotiation situations. But the impact of inputs and planning parameters on outputs generated may be behind the scenes and can be substantial. Naturally, outputs are highly dependent on the data used and targets set, and considerable work has been done with respect to biodiversity surrogates (Lombard 1995; Csuti et al. 1997; Freitag et al. 1998; van Jaarsveld et al. 1998; Reyers & van Jaarsveld 2000; Reyers et al. 2001; Margules et al. 2002; Sanderson et al. 2002; Sarker & Margules 2002; Williams et al. 2002; Gaston & Rodrigues 2003; Lombard et al. 2003) and the setting of appropriate conservation targets (Soule & Sanjayan 1998; Williams 1998; Pressey et al. 1999; Gaston et al. 2002). However, the additional input parameters in conservation planning software platforms are little known or studied. Further documentation of the sensitivities of conservation plan outputs to input parameters and inclusion of this sensitivity and awareness in capacity building exercises are required.

Concerns regarding sensitivity of outputs to input parameters in C-Plan are largely limited to an appropriate combination size and the rules used in selecting areas. By using a variable combination size report, the combination size at which the number of irreplaceable sites stabilises can be determined, the true irreplaceability resolved and an exaggeration of the irreplaceability values avoided. With regards to the minimum set selection procedure, appropriate rules for minimum sets are likely to depend on different data sets and requires exploration, particularly as these intuitive iterative area selection algorithms are very useful and widely used. C-Plan's relatively user friendly, fast and fairly robust approach to evaluating the importance of sites to meeting biodiversity targets and to selecting areas in a manner that is fairly intuitive is limited when addressing spatial targets and minimising the opportunity costs of achieving conservation targets across a whole region (Moore et al. 2003). C-Plan is not designed as a true trade-offs approach to perform or present trade-off scenarios between biodiversity and other socio-economic goals (Pressey 2003). It is suggested that more complex problems might benefit from other algorithms that simultaneously consider costs and spatial constraints, such as simulated annealing algorithm in MARXAN (Possingham et al. 2000).

The simulated annealing algorithm available in MARXAN has numerous strengths. One of them is in fact the strength and capacity inherent in this software platform due to the multiple objectives and thus parameters that can be included. Including the costs of various features and spatial constraints can be important in developing more effective reserve systems (Ardron et al. 2002). MARXAN does provide better solutions to representing biodiversity features when opportunity costs (e.g. cereal production potential) must be minimised. The algorithm's ability to allow bad changes to the reserve system in the beginning increases the opportunity of finding a solution closer to the optimal solution. Finally, the provision of a variety of solutions that meet the conservation objectives provide the ability to explore flexibility and a number of different options available for solving conservation problems (McDonnell et al. 2002; Leslie et al. 2003). Optimality may not always be achievable and the ability to evaluate a range of reasonably good solutions in the context of other considerations, such as foregone opportunity costs, is crucial (Possingham et al. 2000).

The number of input parameters in MARXAN are however more numerous, and outputs are naturally sensitive to their setting. Studies have considered the setting of the boundary length modifier (Possingham et al. 2000; Ardron et al. 2002; Leslie et al. 2003; Stewart et al. 2003), and to a lesser extent conservation feature penalty factors (Ardron et al. 2002) and spatial targets, which has facilitated the more educated use of this software platform by subsequent users. Even with regard to the site costs, most simulated annealing studies have defined the cost as the area of the site (Ardron et al. 2002; Leslie et al. 2003; Stewart et al. 2003). Assigning site costs such as cereal production data, where a number of sites have zero cereal production potential, pose different problems. The same is then true for setting cost thresholds, which have not been explored in published literature. The unusual increase in the cost to cereal production in reserve solutions for which cost thresholds are set requires further investigation, as does the balance between different penalties in the objective function. Conservation feature penalty factors that are too low can be outweighed by cost threshold penalties leading to the under-representation of some biodiversity features. The setting of fixed annealing schedule also requires technically competent users to spend some time searching for appropriate parameters. In addition to using simulated annealing, the sensitivity of reserve solutions to post selection algorithms is not clear. The careful consideration of these numerous planning parameters, for both the objective function and annealing schedule, is one of the negatives of simulated annealing. CLUZ then provides a useful interface to MARXAN, as it limits the number of planning parameters that can be altered, thus standardising certain parameters at values that are considered reasonable in most solutions (Smith 2004). It is suggested that the degree to which reserve solutions are affected by the pre-defined parameters currently prescribed in CLUZ should still be explored.

Both algorithms have important roles to play in conservation planning. The choice of area selection algorithm and methods will depend on the size of datasets, the biodiversity feature targets, the required analysis time and the importance of finding an optimal solution (Pressey et al. 1997). There is a certain degree of integration possible between C-Plan and MARXAN software platforms, which may facilitate the optimisation of C-Plan reserve configurations in MARXAN, and the generation in MARXAN of different starting points for C-Plan (Pressey 2003). However, the use of MARXAN through C-Plan can be quite 'buggey'. Careful consideration of all input parameters is crucial due to their substantial influence on the reserve solutions generated and their determination can be quite confusing. It is an important point that algorithms and the results that they generate are used as tools in combination with input from scientists and conservation managers and not as definitive selections of areas on their own (Pressey and Cowling 2001). We are aware of initiatives to synthesize and review conservation planning software and come up with suggestions of which to use when. We find that with the determination of the necessary planning parameters, simulated annealing options available in MARXAN do provide good answers to complex conservation problems. Overall however, there is still a real need for documentation on best and current practise in MARXAN and on the sensitivities of the algorithm to variation in data types and uncertainty, and of reserve solutions to the different planning parameters (Possingham et al. 2000).

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SUMMARY

Summary and Conclusions

The Gariep basin includes an important region for cereal production. Regions with high cereal production potential are in the central eastern half of the basin, predominantly in the grassland biome. Biodiversity feature richness is also higher in the eastern regions of the basin. Agriculture has been a long-term pressure on biodiversity and spatial overlap between biodiversity and cereal production in the Gariep basin is expected. Comparison of the relative importance of sites to both biodiversity conservation and cereal production has however been limited by the lack of a common currency of measurement between them.

Using targets for biodiversity features set in previous national assessments and developing first attempt estimates of targets for cereal production potential, chapter two shows how, with spatially explicit data on the distribution of both biodiversity and cereal production potential, the importance of a site to meeting either target can be determined using the measure of irreplaceability. Irreplaceability offers an easily understood measure of the importance of sites for achieving specific objectives and although originally applied to biodiversity, it has application for other land-uses. While cereal production potential for different cereal types was combined in this study, irreplaceability could be applied if spatially explicit data for different cereal types were available. The value of irreplaceability would then move beyond just highlighting areas of high richness (or high cereal production potential such as in this thesis) but could highlight areas of rarity, where perhaps specific cereal types are only grown in certain areas. With spatially explicit data for different cereal types, more accurate targets and estimates of future demand could be set. The irreplaceability of sites to cereal production potential increases as cereal demand increases but better data on cereal production potential, especially for different cereal types, will likely highlight slightly different areas as cereal demands increase. Specific cereal types could pose slightly different pressures on biodiversity and offer different options for conservation-friendly management. Comparing the irreplaceability value of a site to different objectives, the potential for conflict between objectives is identified. Sites with high irreplaceability for cereal production that also have high irreplaceability to biodiversity are sites with high potential for conflict. These are areas where trade-offs of some sort seem inevitable. However at the broad scale resolution of this study, finer-scale planning will be required to truly assess the degree of overlap and need for trade-offs. The areas with potential for conflict lie predominantly in the central and eastern grassland biome of the Gariep basin where spatial overlap was expected.

Areas of high potential conflict can sometimes be avoided with systematic conservation planning. Conservation planning approaches have come a long way through the development and application of algorithms and software platforms that can grapple with large, complex conservation problems. Part of the complexity inherent in conservation problems is the need to integrate regional biodiversity and social-economic factors into conservation plans. South Africa is at the forefront of conservation planning and implementation (Balmford 2003) and numerous regional and national assessments in South Africa and across the world have utilized C-Plan (NSW 1999; Pressey 1999). C-Plan offers a relatively user friendly, fast and fairly robust approach to evaluating the irreplaceability of planning units to meeting biodiversity targets in particular and to selecting areas in a manner that is fairly intuitive. These characteristics have contributed towards C-Plan's success as a conservation planning tool in negotiation situations. However C-Plan's ability to incorporate the opportunity cost of sites in the process of selecting sites as part of a possible reserve network is limited to simple heuristic algorithms. The minimisation of cereal production potential as a second selection criteria in this heuristic does decrease the cost to cereal production potential and the number of sites with potential for conflict, but these solutions are predictably less area efficient. Better area selection approaches that can provide a true trade-offs approach exist.

An alternative approach to local heuristics is offered by MARXAN, which is another freely available and increasingly popular conservation planning software platform. At the commencement of this thesis no-one in South Africa had yet used MARXAN. With recent introductory workshops on using MARXAN and CLUZ (the ArcView interface extension with MARXAN - Smith 2004) there is considerable interest in the application of MARXAN to conservation planning problems in South Africa. Its application thus far has largely been restricted to the Australian marine conservation planning arena with emphasis on the software platforms ability to consider spatial targets and constraints. MARXAN uses an objective function to determine a score, calculated as a combination of the cost of the sites selected and a penalty for violating various criteria (i.e. how good a set of sites is as a reserve solution). It is thus able to consider multiple objectives of achieving cereal production potential and biodiversity conservation targets simultaneously. The penalty always includes the representation level for each conservation feature target but can also include a penalty for exceeding a cost threshold (the maximum cost to cereal production potential that can be incurred by a set of sites) or a penalty for not achieving certain spatial fragmentation targets. Simulated annealing is the algorithm mainly used to select areas for which an objective function score is calculated. Simulated annealing has been successful in finding near-optimal solutions to complex problems (Possingham et al. 2000; Stewart et al. 2003). The manner in which simulated annealing does this means that numerous solutions can be generated for the same problem, unlike the single solution usually generated in C-Plan. This would be useful in negotiation situations and in discussion over the flexibility of options and trade-offs.

Chapter three evaluates reserve solutions with different cereal production thresholds (which if exceeded, will impact on the ability of the Gariep basin to meet its cereal production targets) and different conservation feature penalty factors (which prescribe the importance of each conservation feature achieving its target). A fine balance exists between penalties for conservation feature representation, any excess of the cost threshold and finding a good solution. For instance, conservation feature penalty factors that are too low do not guarantee the representation of all conservation features when cost thresholds that are easily exceeded (low cost thresholds) are applied strictly. In some cases, no cereal production cost threshold was set. In these cases, reserve solutions incurred a lower cost to cereal production than solutions that were guided by cost thresholds. Solutions for which no cost threshold was set are considerably more area intensive, particularly in the dry western half of the basin. The application of the cost threshold function seems to generate more area efficient solutions although not necessarily more cost efficient. It is uncertain why the cost threshold function seems to minimize area to some degree and it requires further explanation. However, MARXAN cannot minimize area separately to minimizing the cost to cereal production potential without changing the quantitative measure of cereal production potential to include a measure of area. This is problematic if the intention is to set useful thresholds for the cost field. Solutions generated in MARXAN exhibited high variability in the frequency of selection of sites in the central eastern regions of the basin where the algorithm tries to avoid areas with high cereal production potential. However, the achievement of conservation feature targets in MARXAN does necessitate the conservation of a number of sites in the higher cereal production areas of the eastern half of the basin. Trade-offs in this region are unavoidable, although the number of areas that require trade-offs can be minimised in some simulated annealing solutions.

Chapter three illustrates that the Gariep basin has the potential to produce enough cereal to meet minimum and realistic cereal demands. All biodiversity features targeted can be represented with a cost to cereal production potential of between 16% and 24% of total cereal production potential. However the ability of the Gariep basin to conserve biodiversity and produce sufficient cereal will depend on a number of factors that are not explicitly tackled in this thesis. Finer-scale planning will be needed to truly evaluate the need for and degree of trade offs required. The ability of the biodiversity conservation and agricultural communities to incorporate potential changes due to climate change in regional plans and assessments will be crucial to success. Hand in hand with these issues will be the development of technological advancements that assist in increasing cereal production potential without negatively impacting ecosystems. In the end though, the importance of good biodiversity surrogates and good input data for both biodiversity and cereal production potential will be most crucial to good assessments, planning and monitoring. As a means of identifying and evaluating trade-offs using conservation planning software platforms that are widely used and that are freely and easily available, the MARXAN and C-Plan differ in their capabilities and sensitivities.

Chapter four explores these potential sensitivities of and differences between C-Plan and MARXAN in more detail. The chapter does not attempt a true sensitivity analysis of the algorithms used in the software or to either prescribe or make recommendations for the setting of planning parameters for different conservation problems. It focuses on the relative merits and sensitivities associated with the data and software requirements, sensitivities of planning parameters, and general outputs and illustrations of the inclusion of foregone opportunity costs for cereal production potential. Both software platforms make algorithms easy to use, results are illustrated spatially in a manner that facilitates understanding of the importance and selection of areas, and benefits negotiation situations.

Concerns regarding sensitivity of outputs to input parameters in C-Plan are largely limited to an appropriate combination size and the rules used in selecting areas. In offering better, faster solutions when assessing multiple objectives (with different penalties), such as opportunity costs and certain spatial constraints, MARXAN has a greater number of input parameters that require setting. More information on the function, application and potential impact on the reserve solutions generated, as well as more case studies that state the input parameters used explicitly, are needed to guide conservation planners in the appropriate use of this software platform. Most simulated annealing studies have defined a sites cost as its area, while alternative opportunity costs (such as cereal production data) for sites and setting cost thresholds have not previously been explored in the literature. The balance between different penalties in the objective function is reliant on the judgement of the user. The setting of fixed annealing schedule also requires technically competent users to spend some time searching for appropriate parameters. In addition to using simulated annealing, it is not clear how all the post selection algorithms affect the efficiency of solutions.

Strengths of MARXAN however, include its ability to consider multiple objectives simultaneously, thus avoiding the need to place one objective above another in an iterative selection list. Another important strength is the provision of a variety of solutions that meet the conservation objectives, which provides the ability to explore flexibility and a number of different options available for solving conservation problems. CLUZ provides a useful interface to MARXAN, as it limits the number of planning parameters that can be altered, thus standardising certain parameters at values that are considered reasonable in most solutions. CLUZ also easily converts data into formats compatible between C-Plan and MARXAN, thus making it easier to run both software platforms within the same geographical information system project. Once the necessary input parameters have been determined, reserve solutions in MARXAN do find less costly reserve solutions in terms of foregone cereal production, than those selected using a heuristic approach in chapter two. These solutions are considerably more area intensive. The sensitivity of the reserve solutions generated with the application of the cost threshold function is not clear. While numerous good solutions are found, these are not optimal solutions in terms of the lowest cost to cereal production potential.

The choice of area selection algorithms and methods will depend on the size of datasets, the biodiversity feature targets, the required analysis time and the importance of finding an optimal solution. Overall there is a real need for documentation on best and current practise in MARXAN, on the sensitivities of the algorithm to variation in data types and uncertainty, and of reserve solutions to the different planning parameters. Such documentation is needed to guide conservation managers and planners in the use and interpretation of MARXAN, and even C-Plan, results. Careful consideration of all input parameters, even those pre-determined in CLUZ, is still required as their influence on the reserve solutions generated is substantial. The use and interpretation of these algorithms, particularly MARXAN, does require technical expertise, in addition sometimes to specific, fairly extensive datasets and outputs, but choosing a good approach can make a significant and important difference when it comes to implementation and avoiding conflicts and trade-offs. Other algorithms capable of finding solutions using other local heuristic algorithms or truly optimisation algorithms exist but these are the two options freely and most readily available to conservation planners in South Africa. While finding optimal solutions would be of benefit, this was a little beyond the scope of this project, which looked only at freely available, frequently used software for dealing with conflict and trade-offs between cereal and biodiversity. In any case, finding a single optimal solution may not always be the best. The variety of solutions offered in MARXAN, if it provides near optimal solutions, is very advantageous. It is emphasised that each of the methods undertaken in the current study to find agreeable reserve selection methodologies, have their individual short comings and strengths, which should be considered in the various phases of conservation planning exercise, from the beginning to the end stages.

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